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THE PLANETS OF THE SOLAR SYSTEM

M. Ya. Marov

Translation of "Planety solnechnoy sistemy," Nauka Press
Moscow, 1986, pp. 1-320 (UDC 523.4)

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16. Abstract

This book is intended both for the lay person and the would-be scientist. The planets are discussed with a comparision of their basic natural features: mechanical characteristics and parameters of movement, surfaces, inner structure, physical properties of the atmosphere and meteorology. Also general problems of planetary cosmogony, thermal history and climatic evolution are considered briefly. The book is based on Soviet and foreign material, data from spacecraft, Earth optical and radio astronomical measurements and also data obtained from theoretical models.

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From the Author

In deciding to write a popular book, first of all we ask ourselves the question: to whom is it addressed? Of course, we want it read by as large a circle of readers as possible. This means the book must be written simply. However, simplicity must not be identified with excessive simplification which certainly would not satisfy the demanding reader. Here the person familiar with any serious subject (whom the author in his discussion wishes to attract) is certainly not the same as a simply interested reader. Therefore, the author rightfully hopes that his efforts will be multiplied by the patience of a reader trying to become acquainted with sections of science of interest to him.

We intend to talk about one of the extremely interesting and rapidly developing fields of astrophysics -- about studies of planets of the solar system. In the past decade and a half, this field has been favorably affected particularly strongly by the newest means and methods which have been discovered primarily thanks to rocket-space technology. The flights of spacecraft to Venus, Mars, Mercury, Jupiter and Saturn have brought unique information about the nature of these planets, whose volume and importance exceeds the information obtained in the past century by classical means of astronomy observations. An approach has been laid out for a comprehensive, complex study of each of the heavenly bodies closest to us; further development of methods of technical modeling has been achieved for processes and phenomena occurring on surfaces, in atmospheres, in the interiors of planets and in the boundary fields of outer space. This knowledge assists in the discovery of natural principles in the world which is fairly limited by the space scale, the world in which we live, and in the understanding of what has occurred here and in the past and how it will continue in the future. In this knowledge is the key to solving fundamental problems of modern natural sciences related to the origin and evolution of the planetary system.

A comparative study of planets and their satellites -- "moons" -- is of primary significance for understanding the nature of Earth. The conditions which led to the formation of various natural complexes including those favoring the generation and development of life on Earth are still far from clear to us. The search for them assists, primarily in establishing a range of permissible deviations from complex interactions for many millions of years as a result of the ever growing effect of mankind on the environment, outside of whose limits these deviations could acquire a dangerous and irreversible character.

Only a limited circle of specialists are familiar with the significant progress in our knowledge of nature of the planet. The majority of the readers is familiar only with separate, fragmentary materials from a few publications in scientific popular journals. Several books which have appeared in recent years on the history of discoveries, movement, properties of the planets and other aspects of planetary astronomy cannot fully fill this gap. Therefore, it seemed to us useful to discuss all of the most important aspects of modern

1,2,3

planetary research. Here, in distinction from the form of exposition usually used (sequentially for each of the planets) we have attempted to look at the planets by comparing their basic natural features in sections discussing, respectively, the mechanical characteristics and parameters of movement, surfaces, inner structure, physical properties of the atmosphere and meteorology. We will also touch on some of the general problems of planetary cosmogony, thermal history and climatic evolution.

It seems to us that this type of presentation will be the best approach for the modern stage of study where the basic thrust is toward generalization and comparison of information about various natural complexes on the bodies of the solar system, on the discovery of their common or unique features and basic differences. In just this way, we will present the evolutionary approach to the study of Earth, its nearest environs and the Solar system as a whole, on which in the future, physicists and astronomers will concentrate their efforts, devoting themselves to this attractive field of science.

The book is based on a broad amount of material of Soviet and foreign studies, including the results obtained by spacecraft, Earth optical and radio astronomical measurements and also data generalized within the framework of theoretical models. We have included a large number of illustrations among which photographs of planets occupy a basic position; some of the most impressive photographs are of planets and their satellites. The author wishes to express his thanks to numerous colleagues with whom he has conducted studies and more than once discussed different problems of physics of the planets. He would like to take this opportunity to express gratitude to American scientists G. Mazurskiy, D. Morrison, T. Owen, C. Sagan, B. Smith who have sent him photographic surveys taken from spacecraft and he is grateful to the National Aeronautics and Space Administration of the USA for agreeing to their use. It is his pleasant duty to thank V. N. Zharkov who read the manuscript and made a number of useful comments, N. D. Rozman, L. D. Lomakin and I. A. Belousov for their assistance in preparing the materials for the press. Well, to whom is this book addressed? We think that it will attract the attention of those who are interested in the problems of astronomy, geophysics and space research. The book is fully available to the reader who has a secondary education. We have attempted to avoid using mathematical elements and special terminology or give explanations where one has to know astronomical terms in order to understand them. We would hope that the book will be read with interest by specialists in other branches of knowledge, specialists in mixed fields can find in it a good deal of useful information and possibly, desire to become acquainted more deeply with some of the individual questions or subjects as a whole. If these wishes are to some degree met, then we will be satisfied that our goal has been achieved.

Dealing with such a grandiose subject as the planets of the solar system, naturally it is impossible to simultaneously discuss in detail all of its many aspects. In selecting the material, in the specifics of presentation, in the approach to the subject itself, of course there are personal interests and tastes of the author involved.

Truly, some will be given a great deal of attention and others, on the other hand, will be omitted. One reader possibly will see this as an advantage where another will consider the book deficient. We have not attempted to maximally teach the most recent data, because this would be impossible with the overwhelming flow of new information which is characteristic for the modern stage of research into the solar system. Therefore, individual results can already be out of date with the publication of the book. All critical comments and requests about its content will be received with thanks; they can be directed to the following address: 117071 Moskva V-71, Leninskiy Prospekt, 15, Chief editor's office of physical and mathematical literature, Nauka Press.

September 1980.

* * *

The first edition of the book came out five years ago. Since then, the science of planets of the solar system has been enriched by new important results. They particularly pertain to Venus and Saturn.

In 1981, the Soviet automated probes, the Venera-13 and Venera-14 for the first time transmitted to Earth color panoramas of the surface of Venus and they completed a complex experiment in analyzing the element composition of Venusian soil. Information on the characteristics of the atmosphere and clouds of Venus was supplemented, in particular, information on the content of small atmospheric components. In 1983-1984, the Venera-15 and Venera-16 artificial satellites worked in orbit around the planet for more than a year; they were equipped with radar with lateral view and other equipment for conducting surveys and studying the physical properties of the surface of Venus and also the atmosphere under the clouds. The high-quality images of the surface transmitted significantly expanded concepts of the geological past and present of Venus, and gave us access to a better understanding of ways of its evolution.

In 1980 and 1981, the American Voyager 1 and Voyager 2 spacecraft sequentially accomplished flybys in the Saturn system and transmitted to Earth new data on the planet itself, its satellites and rings. Six new satellites were discovered for Saturn; the fine structure of rings and their dynamic properties were studied; images of the icy surfaces of satellites and the morphology of movement in the atmosphere of the planet were obtained.

In December, 1984, the Vega-1 and Vega-2 Soviet automated space probes were launched; their scientific program includes a continuation of the study of Venus using descent vehicles in June 1985 and the study from flight trajectory of Halley's Comet with approach to it in March 1986. The unique possibility of meeting of a spacecraft with this remarkable heavenly wanderer (periodically returning to the Sun every 76 years) and of conducting a number of measurements close to its core is going to be utilized also by western European and Japanese scientists who have launched, respectively, the Giotto and Planeta A craft.

The new results which are well-known today can be studied in the second edition of this book. Also, certain misprints and imprecisions were corrected and certain sections were expanded in order to bring them up to the modern level of knowledge about the bodies of the solar system. We have attempted here to retain the general style of the book, retaining the necessary strictness in analysis of factual material with the simplicity of presenting it. The reader can judge for himself if we have been successful.

April 1985.

Introduction

> What we know is of no use,
> The unknown only is important
>
> J. W. Goethe, Faust
>
> Glue yourself to a star with a cobweb,
> Turn your face to the universe.
>
> N. Zabolotskiy, 1946

Mankind has known about the planets, the "wandering stars" since ancient times. The miraculous visible movement of five bright stellar bodies on the nocturnal sky, clearly separated from the other numerous stars, has long been unexplained; the memory of this remote epoch is retained in the name "planet" which, in translation from the Greek means "wandering."

The first attempts to discover certain principles in these wanderers rested on the development of astronomy and geometry in ancient Greece and in the Eastern countries -- China, India, Egypt. They were directly related to the requirements of navigation on the seas, chronology of the years and creation of a calendar, and also the formation of the initial concepts about the universe. According to Aristotle's cosmology (fourth century B.C.), relying on the planetary theory of Yevdoks Knidskiy developed earlier, the movement of observed planets was explained as uniform non-axial rotation of (one relative to the other) concentric hollow spheres on whose surfaces each planet was attached and at the center, Earth was located. This theory is the reflection of the basic concepts of Aristotle's philosophy, which divided all of the world "under the moon on the shell of Earth" into water, air, fire and ether. A much more strict basis for the geocentric system of the world was found later in the works of an outstanding ancient Greek astronomer and geographer, Claudius Ptolemaeus, who published in the second century B.C. his notable composition entitled "The Great Mathematical Structure of Astronomy in Thirteen Books" -- Al'magest. Relying on the idea of another ancient Greek, scientist-geometer, Apollonius Pergius, who replaced the rotating planetary spheres of Aristotle with circles and thus put forward the theory of epicycles; Ptolemaeus established the law of observed movement of the planets making it possible to predict their positions. In this way, the results of many centuries of astronomical observations were put forward and systematized into a whole set of knowledge of this period. And although the geometric constructions themselves appeared extremely complex, in a natural way it was related to errors in the initial assumptions about the geocentricity of the world and Ptolemaeus' work had a large progressive value. Particularly important was the practical value for navigation and determining geographical coordinates.

The real scientific basis for modern astronomy was laid about fifteen centuries ago by the work of the great Polish scientist, Nicolaus Copernicus (1473-1543). He decisively discarded the geocentric system of Ptolemaeus and replaced it with a heliocentric system of the world, with a Sun at the center and the planets rotating around it; this accurately and simply explains their visible movement. The outstanding work by Copernicus published in 1543 and titled "Rotation of Heavenly Spheres" was truly a revolutionary step which changed the entire development of the science of astronomy. However, it was many more years before the dogma of the scholastics of the Middle Ages reflecting church thinking changed and a true scientific world view was put forward. The astronomical observations of G. Galileo (1564-1642) using the simplest of telescopes which he had built, the theories of movement of planets formulated and mathematically proven by J. Kepler (1572-1630), the transfer from a kinematic explanation of movement in the solar system to a dynamic explanation thanks to the discoveries of I. Newton (1643-1727) with his law of worldwide gravity -- all of this was brilliant confirmation and a true triumph of Copernican science. Moreover, the historical work of Copernicus which was forbidden by the Inquisition was officially restricted for almost 300 (!) years before it was published.

Copernicus' work practically coincided in time with the beginning of the epoch of the great geographical discoveries when concepts about the world expanded at unexpectedly rapid rates beyond the limits of the European continent. It is just in this period that the process of manufacturing production began; this produced a subsequent intensive production development in a number of western European countries. The development of industry produced growing demands for internal and external markets, stimulating the outfitting of numerous maritime expeditions. Thanks to these expeditions, undertaken by several generations of outstanding fleets, it was finally proven that the Earth is round (remembering that this was shown in studies of the Pythagorean school in the sixth century B.C.) and new land and whole continents were discovered; the Europeans discovered unique and even exotic regions and familiarized themselves with the culture of populations of their countries. This turbulent process of discovery and then mastery of new broad territories actually continued right up to the present century when essentially, on our planet no "white spots" remained. But modern aviation has decreased the flight time between continents to just a few hours.

The beginning of the study and mastery of space which began in October 4, 1957, with the launch of the first Soviet artificial Earth satellite was a tremendous achievement for mankind. Our generation participated in this historic achievement. It is difficult to overestimate its importance for astronomy, for science on Earth, for everyday economic activity of man, and finally for culture and sociology. Not touching here on the numerous aspects which undoubtedly are well known to the reader, we mention only that satellites and spacecraft for the first time have made it possible to look at Earth as a planet from space and to begin a study of its various physical characteristics with methods of "reverse astronomy," that is, with the assistance of analogues of those tools which are used by astronomers at observatories when studying the radiation of planets, stars and nebulae. Direct study of numerous processes and phenomena earlier inaccessible, occurring in the near environs of Earth were begun as well as the study of their interaction with the activity of the Sun and the discovery of certain principles. Finally, thanks to the flight of spacecraft, it has become possible to make a comprehensive study of other near heavenly bodies -- the neighbors of Earth in the solar system. This period of "acquaintance" with our heavenly neighbors, with their natural features, begun in the 1960's, can help this be the epoch of great geographical discoveries whose scale is expanding today far beyond the limits of Earth almost throughout the entire solar system.

It is completely obvious that space research has not led to reconsideration of the fundamental concepts based on astronomical observations -- mechanical characteristics of the planet or laws of their movement. On the contrary, these characteristics discovered by classical methods of optical and radio astronomy were brilliantly confirmed and made more precise in a number of cases. However, the flights of spacecraft basically provided a new quality in obtaining information on the physical nature of planets, the special features of the main active natural mechanisms, -- in a word, where ground means of observation are not adequately effective or simply do not exist. Therefore it is possible without exaggeration to say that after a certain period of relative calm, planetary astronomy has now come into a period of Great Renaissance. Planets unfamiliar earlier were discovered; the possibilities and effectiveness of observations grew immeasurably; their range expanded. The conduct of physical experiments directly on heavenly bodies became possible, as well as a detailed geophysical study on Earth, the study of extra-terrestrial matter in Earth laboratories. Such an encroachment of geophysics into the traditional spheres of astronomy, significantly more than occurred earlier, the "accessibility" of the Moon and planets in a natural way brought this section of astrophysics closer to the complex of sciences on Earth and this process will undoubtedly continue in the future.

The historical value of this period in the life of mankind can, to a full degree, be evaluated only by our descendants; truly we can say that just now we are beginning to fully be able to evaluate the scientific feats of Copernicus, Galileo and Newton.

Aristotle's cosmology and the studies by Copernicus are separated from us by almost 20 centuries and the creation of a precise theory of movement of planets until the beginning of flights of the spacecraft then took about three centuries. Studies of the solar system have been continuing for less than three decades and the flow of discoveries is truly astounding. It is fully probably, however, that this process will slow down in the future and the beginning of a new thirty-year period, the renaissance stage of research of distant environs of the planetary system and a detailed study of the near environment of Earth basically will be completed. Right now, such traditional sections of human knowledge as geophysics, geochemistry, geology, meteorology, to a greater and greater degree will become sections of cosmophysics, cosmochemistry, planetology, physics of the atmospheres of the planets, and this will create new attempts for deeper and more comprehensive study of our own planet. Recognition of the significance of problems in space research of Earth and the planets which have been presented to mankind in the 20th century is growing.

THE PLANETS OF THE SOLAR SYSTEM

M. Ya. Marov

CHAPTER I

CERTAIN GENERAL INFORMATION ABOUT THE SOLAR SYSTEM

As I leave a space and enter
the neglected garden of magnitudes,
I cut the imaginary constancy and
the consciouwness of cause and effect.
I leaf through your textbook, infinity,
without man, without people,
Wild leafless healer,
A textbook of enormous radicals.

O. Mandel'shtam, 1933

We will begin our discussion of the planets with some of the /14* general characteristics of the solar system whose members also include other cold bodies -- asteroids, comets, and meteor dust.

The planets are separated from us by tremendous distances, tens and hundreds of millions of kilometers. In order to receive a radio signal on Earth from a spacecraft located close to Venus or Mars, even in the most favorable conditions, one must wait several minutes and then the radio waves like any other electromagnetic radiation are propagated at the speed of light! Within the limits of the solar system as the unit of distance we take the astronomical unit (IAU) that is, the average distance of the Earth from the Sun comprising 149.6 million km. Light covers this distance in 8 min 19 s. The average radius of the orbit of the known planet farthest from us, Pluto, is 40 IAU and in order to reach it, a radio signal sent from Earth requires five and one half hours.

However, the limits of the solar system are not limited by the diameter of orbit of Pluto -- indeed, they significantly exceed it. Starting with purely physical expressions, beyond its external boundary one could take a distance at which flowing of the plasma ("solar wind") occurs in the interstellar gas continuously flowing from the Sun and filling all of the near-Sun space. The boundary of this field is called the heliopause. The problem of infiltration of solar plasma which has a supersonic speed of interstellar gas consisting almost entirely of ionized hydrogen at a temperature of /15

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* Numbers in the margin indicate pagination in the foreign text.

≈100 K was discussed in detail by Soviet physicist V. B. Baranov and K. V. Krasnobayev. It seemed that for an idealized model of a spherically symmetrical plasma flux, this slowdown and formation of a shock wave occurs at distances from 10^3 and 10^4 IAU, depending on the concentration of particles assumed for the interstellar hydrogen in limits 0.1-1 cm^{-3}. Moreover, the configuration formed is an asymmetrical result of movement of the Sun at a velocity of about 20 km/s relative to the nearest stars (and, correspondingly, of the interstellar gas) -- this is the well-known movement in the direction toward the solar apex located in the Hercules constellation. As a result, in the direction of the vector of velocity of the Sun, the impact transition occurs close to the cylinder and in the opposite direction (toward the antiapex), on the other hand, farther from the center. Nevertheless, the evaluation made above of the average characteristic dimension of the heliopause remains true.

In other words, a more correct criterion is the boundary on which the force of gravity of the Sun is compared with the force of gravity of the stars nearest to us. This criterion leads to an evaluation of the dimensions of the solar system on the order of $1.5 \cdot 10^5$ IAU

As huge as these distances seem according to Earth concepts, on the scale of the universe they are comparatively small. Actually, in stellar and galactic astronomy, the measurement units of distance are in light-years and parsecs. The parsec is the distance from which the great pole of the Earth orbit is visible at an angle of 1' (or in other words, the distance to the stars whose annual parallax equals 1'). Consequently, the distance expressed in parsecs is the inverse value of the annual parallax; one parsec = 206,265 IAU (radii of the orbits of Earth) which comprises $30.86 \cdot 10^{12}$ km and equals 3.26 light-years. In these units, the diameter of our planet system is a total of about 0.001 parsecs. Even in relation to the diameter of our galaxy (Milky Way) close to 30 kiloparsecs (30,000 parsecs), this comprises a total of several hundred million parts; and then modern astronomy deals with distances of mega and even gigaparsecs[1]! The galaxies closest to us, the large and small Magellan Clouds, 55 kparsecs away from us and the famous Andromedes Nebula -- /16
0.7 Mparsec from us. Such distances separate us from our farthest galaxies as are observed now and the light from them was emitted before the formation of the Sun -- more than 4.5 billion years ago!

The galaxy has the shape of a gigantic convex lens with thickness about 4 kparsecs and our solar system is found at a distance of about 10 kparsecs (33,000 light-years) from its center in one of the spiral sleeves (Figure 1). The galaxy rotates and the rate of rotation at first increases with an increase in distance from the center and then decreases. The rotation of the Sun around the center of the galaxy occurs at a velocity of about 240 km/s, so that its full rotation is completed in approximately 200 million years.

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[1] Megaparsec (1 Mparsec) = 10^6 parsec;
Gigaparsec (1 Gparsec) = 10^9 parsec.

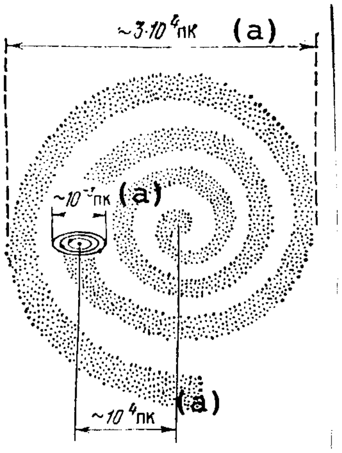


Figure 1. Position of the solar system in the galaxy.
Key: a. parsec

Our Sun which is an ordinary yellow star belongs, according to the classification used, to the spectral class G2, literally lost among many billions of its brothers which are at different stages of evolution; in the galaxy there are approximately $3 \cdot 10^{11}$ stars. Moreover, the relatively small area of space occupied by the solar system is of primary interest to us inasmuch as it is here that processes and phenomena occur which have definite significance for Earth and its near environs. It is primarily from this region that right now we are gaining a concept of space available through direct study of the time period surveyed -- obviously, for a period of the last few centuries.

Taking into consideration the relationships of dimensions in the universe which we have presented, we can consider it paradoxical that up until recently we knew less about the planets than we did about the stars. This primarily involves the inner structure, chemical composition and special problems of classification of planets according to characteristic traits corresponding to one or another phase of evolution, inasmuch as the existing tools were still not available for observing the planets beyond the limits of our solar system. The multiplicity of stars has made it possible even from the beginning of our century to discover fully determined principles of their physical nature and the sequence of evolutionary stages in accordance with the positions on the Hertzsprung-Russel diagram which illustrates the relationship between luminosity and the spectral class of the star. /17

Starting with obvious differences which express the features of formation of the planetary system, the nine large planets can be divided into two basic groups: the planets of the Earth group which, besides Earth, include, Mercury, Venus and Mars, and planets of the Jupiter group or the planet giants which comprises Jupiter, Saturn, Uranus and Neptune. This classification does not include Pluto which in its dimensions and properties is considerably closer to a satellite of the planet-giants. Spacecraft have completed flights to five of the planets (Figure 2).

There are planets besides Venus and Mercury which have satellites. The total number of satellites known today is 53, including those discovered in January 1986 with the flight of the Voyager 2 -- new Uranus satellites. The overwhelming majority of satellites belong to the planet-giants. The largest satellites belong to Earth, Jupiter, Saturn and Neptune. These are our Moon, the four closest satellites to Jupiter discovered in 1610 by Galileo and therefore called the Galilean satellites (Io, Europa, Ganymede, Callisto), the satellite of Saturn called Titan and the Neptune satellite named Triton. In their dimensions, these satellites are

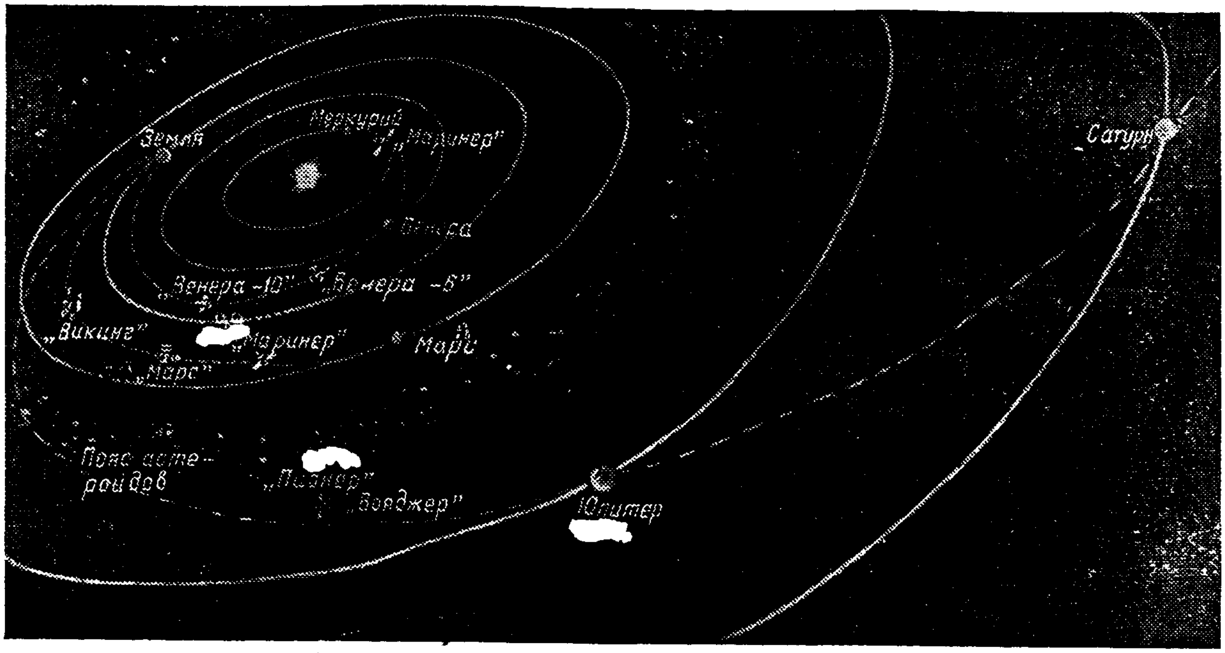


Figure 2. A diagram of flights of spacecraft to planets. Orbits of the spacecraft are shown by the dashed lines. /18
Key: 1. Earth; 2. Mercury; 3. the Mariner; 4. Venus; 5. the Venera-10; 6. the Venera-6; 7. the Viking; 8. the Mars; 9. the Mariner; 10. Mars; 11. belt of asteroids; 12. the Pioneer Voyager; 13. Jupiter; 14. Saturn.

comparable to planets of the Earth group: Io, Europa and Triton are approximately the same as the Moon (its average radius is R=1738 km), and Titan, Ganymede and Callisto--like those of Mercury (its average radius is R = 2439 km). The other satellites have dimensions of a few dozen up to several hundreds of kilometers and, in distinction from larger bodies, have an irregular (non-spherical) shape. This makes them comparable to other similar bodies moving around the Sun and particularly the small planets which are also called asteroids, that is, star-forming objects. In the catalogue, there are about 2300 small planets, including the total number of bodies whose dimensions /19
≈1 km are estimated to be at least 10^5. Of the total mass, however, this does not exceed 0.001 parts of the mass of Earth.

The overwhelming majority of asteroids occupy a broad ring field of space between the orbits of Mars and Jupiter, at an average distance from the Sun of 2.75 IAU. The diameter of this largest of the asteroids -- Ceres -- reaches 1,000 km and after it comes Pallada, Vesta and Gigea with dimensions, respectively, 608 km, 538 km and 450 km. Along with this ring-shaped field which is called the asteroid band, there are groups of asteroids with significantly greater extension in elliptical orbits. Among the 34 largest asteroids which intersect the orbit of Mars in their movement, there are eight asteroids in the Apollo group which in a perihelion goes inside the orbit of Earth, and Icar -- even inside the orbit of

Mercury. If we pay attention to all of the asteroids with dimensions greater than 1 km, which in their movement intersect the orbits of Earth and Mars, then their number will reach approximately 10,000. In turn, in the aphelion, a number of asteroids are removed from the Sun to a distance exceeding the radius of Jupiter's orbit. Such a character of movement brings them close to the short-period comets and gives us the basis for E. Opik's hypothesis that some of the small planets are remnants (relicts) of comet nuclei whose gas component has completely disappeared.

The majority of "tail oddities" -- comets, obviously, which do not have a direct field, are limited to the heliopause and are located beyond its limits. Significantly closer to the Sun we find only a few families of comets; their aphelion lies basically between the orbits of Jupiter and Neptune. At the present time, elements of orbit of about 600 comets can be counted among which are short-period (period of rotation less than 200 years) and long-period (with period more than 200 years). At the same time, the total number of comets is estimated at a value of 10^{12} -- 10^{15}. The basic family, as the Dutch astronomer J. Oort proposed is concentrated in the field of comet clouds located in the galactic plane at a distance of $\approx 10^5$ IAU from the Sun. This cloud hypothetically formed simultaneously with the formation of the solar system and its total mass, obviously, does not exceed one mass of Earth.

Other hypotheses exist about the origin of comets which include one which deserves attention, the "theory of focusing." It is /20 proposed that in its own movement, the Sun intersects interstellar gas-dust clouds and individual large "clusters" are focused on the solar trajectory (the "axis of accretion"). The basis for this hypothesis is the well-known concentration of perihelions of comet orbits in the environs of the solar apex and anti-apex. Moreover, this concentration does not contradict the hypothesis of clouds if one pays attention to the probable effect of "cracking" of the comet matter as to interstellar gas. Within the framework of this hypothesis, focusing explains with more difficulty the predominance of elliptical and not hyperbolic comet orbits and certain other features which we will not pause to discuss. Therefore, the hypothesis of a ring-shaped comet cloud, often called the Oort cloud, is for us more basic.

Truly one should remember that recently molecular interstellar clouds were discovered lying close the galactic plain with tremendous masses, up to 10^6 $M_\odot$ ($M_\odot$ -- mass of the Sun) which could be evidence of the strong perturbation effect on Oort's cloud when the solar system with its movement toward the apex passes at distances from it of less than approximately 10 parasecs. This brought up the possibility of its prolonged existence, commensurate with the age of the solar system, at such a great distance from the Sun. Avoiding this difficulty is possible, however, having assumed that the dimensions of the Oort cloud is less, that is, it is at a distance on the order of $5 \cdot 10^4$ IAU, possibly, even at a distance of 10^4 IAU, where perturbation is not so great.

An alternative to the cloud of interstellar gas is the hypothesis of the existence on the Sun of a companion in the form of a dwarf star approximately 9 times the visible stellar value (9^m), found in a very eccentric orbit with maximum distance (at the apastron) up to 2.5 light-years and with a period of rotation relative to the Sun of 26 million years. It was even given the name Nemezides. If this object actually exists, then approaching the Sun (in the periastron) it must strongly perturb the comet cloud, "throwing" millions of comets inside the solar system, many of which could intersect, in particular, with the orbit of Earth. It is interesting here to note that as paleontologists have observed, the disappearance of certain biological types on Earth occurred over a period of 26-31 million years; it is tempting to relate to the periodicity of the grandiose climatic changes on Earth due to the sharp increase in dust content as a result of impact with comets. A similar periodicity is detected in the increased content (up to a magnitude of 2) of the rare element -- /21
iridium -- in the surface layers of the crust which also can be due to such catastrophes.

In spite of the fact that there are actually sources of perturbation, for us it is important to understand that under their effects the comets from the cloud can have orbits in which the distance to the perihelion is small and pass, in this way, close to the Sun where it will reach the greatest brightness and one will be able to detect them. A similar example is observed in short-period comets with closer aphelions. The extended tail illuminated in solar rays is formed due to a loss of mass by the core of the comet comprising, according to the generally accepted model now by the well-known American astronomer, F. Whipple, of a "dirty snow," that is, water ice along with frozen dust and larger individual fragments of rock. The tail is part of the gas-dust atmosphere (this so-called comma of the comet occurring as it approaches the Sun), which "is blown" in an antisolar direction under the effect of light pressure. At the same time, the dimensions of the core do not exceed 5-10 kilometers, the developing tails extend for distances of hundreds of thousands and millions of kilometers. The maximum loss of mass due to one rotation in the brightest comets is estimated at a value of 0.2-0.5% (usually less than 0.1%) and therefore often the comets passing close to the Sun cannot live long. In turn, the disappearance of gases and dust as a result of sublimation of the comet core (that is, transfer of matter from a solid state to a vapor, omitting the liquid phase) creates additional perturbations due to the reactive force applied on gravitational perturbations of the Sun and planets. All of this leads to the fact that the parameters of comet orbits (eccentrics, accumulation) lie within broad limits. Here difficulties are involved in predicting the moments of occurrence and observation of these heavenly bodies, the suddenness of their appearance. It is interesting to note that perturbation in a perihelion at a distance of 1-2 IAU imparts a large pulse to the movement of the comet rather than slowing of the artificial Earth satellite in the perigee of a comparatively close elliptical orbit. Due to this, the aphelion /22
distance changes greatly.

Some of the comets which appear, having undergone strong perturbations close to the perihelion, even transfer from an elliptical to a hyperbolic orbit and always leave the solar system.

In recent times, the interest in comets has grown considerably, due to the next arrival at the Sun of one of the best known of the periodic comets -- Halley's Comet. This event occurs once every 76 years; the last time was 1910. Spacecraft are being sent to meet the comet for the first time; this includes the Soviet Vega-1 and Vega-2. For successful conduct of these complex experiments with flyby from the core at a distance of a total of a few thousand kilometers, it is necessary to know with high precision the parameters of movement of the comet itself; a broad international network of observations has been organized for this purpose and non-gravitation perturbations are being calculated theoretically.

Besides the bodies we have considered, in interplanetary space there is an even larger quantity of particles of different dimensions, primarily very small, in mass thousands and millions of parts of a gram. They are called meteor dust. The formation of these particles is dues to the fact that, in all probability, collisions of larger bodies (asteroids) and sequential crushing into smaller fragments occurred for the entire length of existence and evolution of the solar system. Also, a random breakdown of such bodies under the effect of temperature deformations or rapid inherent rotation also makes a definite contribution.

Meteor dust is recorded both as flares and by observing radar reflections from the remaining traces during invasion into the upper atmosphere of Earth and directly into the experiments on high altitude rockets of the artificial Earth satellites and interplanetary probes. Their existence involves the well-known phenomena of zodiacal light -- a weak diffuse illumination symmetrical relative to the plane of elliptics. It is observed in the form of cones expanding toward the horizon soon after the onset of darkness or before dawn and rapidly they disappear as the angular distance to the Sun increases. The illumination occurs thanks to scattering of solar light on the particles of dust caught in near-solar orbit and forming, according to our modern concept, clouds in the shape of ellipsoids, one of which serves as a focus for the Sun. The content of dust in such a cloud /23
must decrease with an increase in distance from the Sun and from the plain of the elliptics.

Moreover, a number of additional effects significantly change this model. This means that for distribution of dust, along with gravitational forces, there is an effect of the force of light pressure on the Sun, mechanical breaking and also an electrical charge acquired by the particles. Under the effect of pressure of solar radiation, the finest particles of dust are swept out into the external field of the solar system. The larger particles (in units of hundreds of microns) are subjected to the so-called Poynting-Robertson effect whose contribution is comparable to the mechanical braking of interplanetary gas for particles of even larger dimensions. Additional braking is created by the formation on the particles of electrical charges and then Coulomb forces occur in the electrical field and Lorentz forces during their interaction with the interplanetary magnetic field.

The physical essence of the Poynting-Robertson effect consists of the following. A particle absorbs solar photons moving at the speed of light $\underline{c}$ radially from the Sun and therefore having a zero moment of quantity motion relative to it. At the same time, it emits energy uniformly in all directions, that is, isotropically, so that a pulse is partially transmitted by the photon emitted which has a particle itself. As a result of this, the particles in which the vector of velocity $\underline{v}$ and, consequently, the pulse are directed tangentially toward its trajectory; it acquires in the inherent system coordinates of an additional component v/c caused by light pressure and a direction opposite its movement. In this way, due to the decrease in moment of the quantity of motion of the particle, a gradual decrease occurs in the radius of its orbit and it approaches the Sun as a spiral, that is to say, it "falls into the Sun." In other words, the motion occurs not according to the Kepler ellipse because a non-central force is acting on the particle. It is easy to calculate the "lifetime" of the particle in near-solar orbit if one uses the appropriate simple formula. According to the theory, a spherical particle with radius $\underline{r}$ and density ρ^*, primarily being in an almost circular orbit with radius $\underline{a}$ is incident on the Sun for a time /24
$t_* = 7 \cdot 10^6 r\rho^* a^2$ years. Consequently, for particles with $r \approx 100$ μm and $\rho^* \approx 3$ g/cm^3, found from the Sun at a distance of $a \approx 1$ IAU, the lifetime comprises $t \approx 3 \cdot 10^4$ years. At the same time, the particle does not reach the Sun but evaporates in its environs and goes into the composition of the solar atmosphere. Obviously, the Poynting-Robertson effect basically is explained by the actual absence of dust in the inner fields of the solar system. In actuality, flights of interplanetary spacecraft do not show any kind of noticeable changes in its content up to the orbit of Jupiter including (which is extremely interesting!) the field inside the asteroid band. Micrometer sensors on the Pioneer and the Voyager hardly detected any changes in the count rate here, having discovered a small increase in concentration only in direct proximity to Jupiter itself.

Let us note that separate relatively small fields with increased concentration of dust material can exist in a system of two attracting centers (Sun-planet, planet-satellite) at points of relative equilibrium -- the so-called points of liberation or Lagrange points named in honor of the remarkable French mathematician, P. Lagrange who predicted their existence back in the 18th century. The position of these points is shown in Figure 3. Only the "triangular" Lagrange points L_4 and L_5 are stable here; they are equidistant from both centers, that is, lying at an angular distance of approximately 60° along the orbit of the satellite of the central body on both sides of the satellite and forming two equal-sided triangles. Once again, they are of the greatest interest from the point of view of "traps" for the dust material and for capture of the larger bodies. The report on detection of an increased content of the dust in the environs of these points for the Earth-Moon system was made in 1961 by Polish astronomer K. Kordylevskiy. At points L_4 and L_5 on Jupiter's orbit, there is a

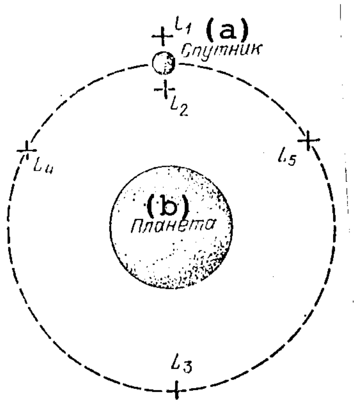


Figure 3. Position of the Lagrange points. L_1 -- L_5 in the planet-satellite system.
Key: a. satellite; b. planet.

well-known group of asteroids -- the so-called Trojan group. Small asteroid-like bodies /25 were also detected at the Lagrange points of two fairly large Saturn satellites -- Tephiya and Dione.

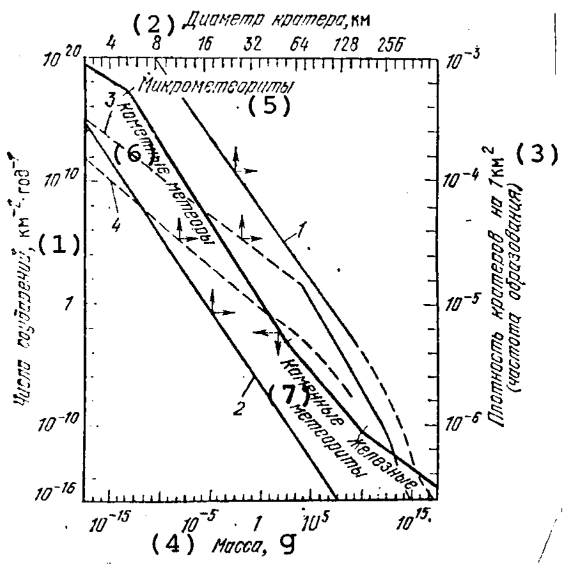
In the capture zone of Earth, particles of different mass and dimension are incident. They practically all must collide with it and therefore a noticeable concentration of dust close to Earth cannot occur. This is well confirmed by a series of experiments on satellites essentially verifying the earlier measurements and concepts not confirmed about the dust band. For most of the particles, their collision with Earth ends in evaporation in the surface atmosphere (basically at altitudes of more than 80-120 km) but a certain quantity reaches the surface of Earth in the form of well-known meteorites. It is completely obvious that the larger the body the much smaller the probability of such an event. According to the existing analysis of the flux of the finest dust particles going to Earth, it is primarily isotropic and comprises in mass about 10^{10} g/day, that is, 10^4 g/day or about 0.1 t/s. The surface of Earth $S = 4\pi R^2 \approx 5 \cdot 10^{18}$ cm^2, the velocity of meteor particles lies in a range 11-72 km/s. Assuming an average velocity $v \approx 30$ km/s, we find that the density of the dust component in near-Earth space comprises

equation $$\rho = \frac{10^5 \text{ g/s}}{5 \cdot 10^{18} \text{ cm}^2 \cdot 3 \cdot 10^6 \text{ cm/s}} \approx 7 \cdot 10^{-21} \text{ g/cm}^3.$$

For comparison, let us point out that the density of the Earth atmosphere at an altitude of 1000 km is $\rho \approx 5 \cdot 10^{-19}$ g/cm^3, that is, at least a magnitude of two larger.

The study of meteor bodies is of great independent interest, but with them are directly related general problems of evolution of larger space objects, in particular, the formation of surface planets and asteroids.

We are talking about particles incident in the zone of capture of heavenly bodies, whose maximum case is incidence of particles on that body (or meteoroid on the planet). The dynamics of approach and collision is considered within the framework of the theory of elliptical orbit generalized for a hyperbolic orbit. In turn, distribution of a number of collisions depending on mass, that is, fluxes of meteor bodies with different dimensions than mass can be shown in the form of diagrams as presented in Figure 4. This diagram is attained on the basis of many years of systematic observations of meteor bodies on the basis of paleontology data, theoretical extrapolations, and in recent times -- with the calculation of direct studies which have become available of the surfaces of planets and their satellites. It is used not only for evaluation of the fluxes of



meteorite bodies on Earth but also primarily for evaluating the probabilities of collisions with any of the heavenly bodies of interest to us and in this way for judgment of the density and distribution by dimension of craters on their surfaces. The results of the appropriate statistical analysis for the surfaces of the Moon and Mars made by V. Hartman (curves 1-4 in Figure 4) are found in good agreement with this program. In the section discussing the surfaces of planets, we will return to this interesting question.

Figure 4. Fluxes of meteor bodies depending on mass (fat curve) and distribution of density of craters (per one km^2 depending on their diameter on the Moon (1 -- for continents and 3 -- for seas) and on Mars (2 -- for seas and desert and 4 -- for polar fields). The arrows indicate which axes should relate to the appropriate curves.
Key: 1. number of collisions, $km^{-2} \cdot year^{-7}$; 2. diameter of the crater, km; 3. density of craters per 1 km^2 (frequency of formation); 4. mass, g; 5. micrometeorites; 6. comet meteors; 7. rock iron meteorites.

CHAPTER II

THE BASIC MECHANICAL CHARACTERISTICS OF PLANETS AND SPECIAL FEATURES OF THEIR MOVEMENT

Nothing in all the universe
Exists, only their flight,
And it carries me far off, impressed
Flight of the planet, the Earth, the stars, flight and stones
And my thoughts on life and on death --
On two wings, on two waves they float.

Paul Eluar
"Repetition," 1922

Let us go now to the basic subject of our discussion about the /27
solar system -- the large planets. We begin with their main mechanical characteristics on whose study the basic efforts of many generations of astronomers have been concentrated. The fundamental importance is primarily, knowledge of geometric dimensions, mass (and consequently, average density), the parameters of orbital motion of the planets and their satellites and the parameters of rotation. The latter directly involves determination of the figures of the gravitational body and limits of deviation of its gravitational field from spherical symmetry. In turn, the knowledge of the shape and degree of its correspondence to hydrostatic equilibrium is a determining factor when constructing models of the inner structure of planets. The set of all of these characteristics among which one observes a number of important features is given a good deal of attention quite purposefully: essentially, they all play an important role in the problem of planetary cosmogony.

Dimensions, Mass, Rotation

Figure 5 shows the position of orbits and relationships of dimensions of the planets. In the astronomy of planets found inside the orbit of Earth, that is, close to the Sun, we name the lower and outside of Earth's orbit -- the upper. Their basic mechanical characteristics are shown in Table 1 to which we will refer constantly in the future. It is apparent from Table 1 that the main difference among planets of the Earth group and the planet-giants is in their dimensions, mass and density. The difference in dimensions is about /28
one-and-one-half magnitudes and in mass -- it reaches almost four magnitudes. With significantly larger dimensions in mass of the planet-giants, they have four or five times less density than planets of the Earth group. This is explained by the differences in the relationships of the three basic types of matter of the planets -- gases, ice and rock or, as we have already said, mineral rock (among the most important are iron, silicate and oxides of magnesium, aluminum, calcium and other metals).

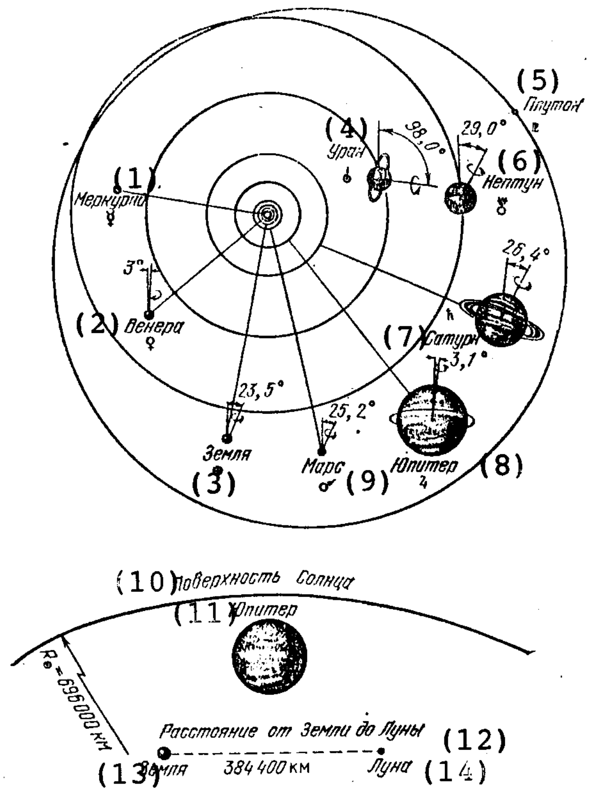


Figure 5. Comparison of the orbits and dimensions of planets in the solar system.
Key: 1. Mercury; 2. Venus; 3. Earth; 4. Uranus; 5. Pluto; 6. Neptune; 7. Saturn; 8. Jupiter; 9. Mars; 10. surface of the Sun; 11. Jupiter; 12. distance from Earth to the Moon; 13. Earth; 14. the Moon.

For a long time, optical observations were the only means for determining the geometric dimensions, the parameters of rotation and other characteristics of the planets. /29 The position of the planet in the orbit relative to the observer on Earth is characterized by a phase angle which is formed by the direction from the center of the planet to the Sun and Earth. In the low planets, Mercury and Venus, the phase angle changes from 0° in the upper conjunction to 180° in the lower conjunction when the planet is as close as possible to Earth and the non-illuminated hemisphere is turned toward it. The best conditions for observations begin at the greatest distances of the planet from the Sun (the greatest elongation). The phase angle of the upper planets (from Mars to Pluto) changes from 0° in conjunction and in the opposite to a certain largest value $_m$ in quadratures. The best conditions for observation begin in the opposite position (opposition) when observing the approach of the planet to the Earth.

Unfortunately, ground optical measurements have limited precision, particularly in the presence of planets with atmosphere and clouds. The most accurate results when determining geometric dimensions are produced by a method of covering a star which would make it possible to be fairly precise, in particular, for the diameters of Neptune and Pluto. This applies to calculation of mass which is particularly difficult for Venus and Mercury due to the absence of satellites; estimates according to methods of perturbation applying to the nearest planets involved significant errors. Particularly great difficulties are involved in determination of the mass of Pluto due to the smallness of its effect on the movement of its much more massive neighbors. Obviously, the estimates obtained earlier of the mass of this planet on the basis of theoretical calculations by well-known

TABLE 1. BASIC CHARACTERISTICS OF THE PLANETS

Planet	Average heliocentric distance (large orbital half-axis) IAU	Eccentricity	Inclination of orbital plane to. ecliptics, degr	Sidereal period of rotation (in Earth years)	Period of rotation (in Earth days, d or hours, h)	Equatorial radius, R_e km	Volume (⊕=1)	Mass, M (⊕=1)	Density, γ, g/cm^3	Inclination of equator tow. orbital plane, degr.	Direction of rotation	$I = \frac{C}{MR_э^2}$	Albedo	Effective temp., K	Number of satellites
Mercury	0,387	0,206	7,0	0,24	$58,6^d$	2439	0,05	0,06	5,44	<30°	Forward	0,324	0,09	435	none
Venus	0,723	0,007	3,4	0,62	243^d	6051,5	0,90	0,82	5,24	177°	Reverse	0,332	0,77	228	none
Earth	1,000 ($1,5 \cdot 10^8$ km)	0,017	0	1,00 (365,26 dy)	$23,9^h$	6378	1,00 ($1,08 \times 10^{12}$ km^3)	1,00 ($5,98 \times 10^{24}$ kg)	5,52	23,5	Forward	0,332	0,30	255	1
Mars	1,524	0,093	1,8	1,88	$24,6^h$	3394	0,15	0,11	3,95	25,2	Forward	0,375	0,20	216	2
Jupiter	5,203	0,048	1,3	11,86	$9,9^h$	71 398 **)	1318	318	1,33	3,1	"	0,262	0,42	134	16
Saturn	9,539	0,056	2,5	29,46	$10,2^h$	60 330 ***)	755	95,1	0,69	26,4	"	0,227	0,50	97	17
Uranus	19,182	0,047	0,8	84,01	$24^h \pm 4^h$ *)	25 400	63	14,6	1,26	98	Reverse	0,212	0,50	54	14?
Neptune	30,058	0,009	1,8	164,8	$17,8^h$ *)	24 750	58	17,2	1,67	29	Forward	0,200	0,50	38	2
Pluto	39,439	0,250	17,2	247,7	$6,4^d$	1500	0,01	0,002÷÷0,004	0,70÷÷1,20	?	"	?	0,40	32	1

*) According to the latest data.

**) Value corresponding to the level with pressure in the atmosphere of 1 bar obtained on discovery of the β Scorpion.

***) At a level with pressure 1 mbar (1 bar = 0.986 923 atm = 10^5 N/m^2, 1 mbar = 10^{-3} bar)

[Commas in tabulated material in this table and in succeeding tables designate decimal points].

astronomers V. Pickering and P. Lowell (averages between masses of Neptune and Earth) were much too high. The very first datum of observation which did not permit measuring the disk of Pluto led us to this same conclusion -- it proved to be less than 0.2", and the mass considerably smaller than the mass of Earth. This forced us to reconsider the degree of its perturbation effect on the movement of Neptune. Therefore, even by 1930, that is, immediately after the discovery of Pluto by C. Tombaugh at the Lowell Observatory in Flagstaff, E. Brown pointed out the basic hypothesis that the fact of the discovery of Pluto itself was not due just to a happy chance. This opinion was confirmed by a majority of modern astronomers including D. Cruikshank and his colleagues from the Observatory of Kitt Peak and the observatory of the University of Hawaii. The values presented in Table 1 of the albedo and the dimensions of Pluto were obtained from an analysis of the results of their careful spectrometric observations. /30

The report in July of 1978 about the discovery of a Pluto satellite in photographs obtained by D. Christie was a sensation; Christie used a 155-centimeter telescope at the Marine Observatory in the USA. The resolution on the photographs does not permit distinguishing the presence of bodies close to Pluto, the bodies moving with in orbit but an elongated image with a large projection made it possible. However, an alternative satellite was difficult to find, because it had the same shape as Pluto itself and recently had been broken by centrifugal forces. From an analysis, it follows that the satellite is turning in orbit around Pluto with a period equal to the period of rotation of the planet itself at a distance of ≈17,000 km from it (such is the linear dimension of the image). This distance and estimate of distance to the center of mass of the Pluto-satellite system leads to a value of the mass of the latter on the order of 1/30 mass of the planet. This ratio exceeds the ratio of the /31
mass of Moon and Earth by almost two (1/81.4) and means that the Pluto satellite (which has been named Charon) must have a fairly significant effect on the planet. The existence on Pluto of a satellite, obviously, found in synchronous orbit (which is a unique example of a natural synchronous satellite in the solar system) gives us the basis for talking not about a separate planet but about a close dual system. In turn, this has made it possible to more precisely determine the mass and density of Pluto itself (see Table 1).

In precision of mass with equatorial radius and average density of Mercury, Venus, Mars, Jupiter and its Galilean satellites, the radar measurements and flights of spacecraft have made a decisive contribution. As a result of analysis of the perturbing effects on the flight trajectory of a spacecraft or orbit of an artificial satellite, the planets also have significantly more precise parameters for their gravitational fields. In the expansion of the gravitational potential of the planet according to spherical harmonics, several primary members are determined which characterize the perturbing effects due to the difference in the field from the central field. At the same time, significant progress is being achieved in determining the shape of the planet, the degree of its deviation from the spheroid and a number of dynamic characteristics directly related to the parameters of rotation.

From Table 1, it is apparent that with the large mass of a planet-giant, the smallest periods of rotation occur as a result of which linear velocities on the equator of the visible surface are great (12.2 km/s for Jupiter at the same time that on Earth it is 0.46 km/s). This is due to the fact that, in particular, there are significantly large values of dynamic compression of these planets in comparison with planets of the Earth group defined as $\alpha = \frac{a - b}{a}$. Here a and b are the large and small half-axis of the ellipsoid rotation for which, in a first approximation, one must satisfy the shape of a rotating planet found in a state of hydrostatic equilibrium. In this way, the value of α characterizes the distribution of density in its interior (for a non-rotating planet it would be spherically symmetrical). In turn, the true shape of the planet is determined by a geometrical compression in $e = \frac{\bar{a} - \bar{b}}{\bar{a}}$, which characterizes the actual oblate shape of the planet determined by the difference in equatorial $\bar{a}$ and polar $\bar{b}$ radii. The compression of Jupiter comprises 4400 km at the same time that for Mars it is about 25 km and for Venus it does not exceed a few hundreds of meters. One must emphasize that if for Jupiter and Saturn (as results of analysis of measurements of trajectory of movement close to these planets has indicated recently) e and α agree well with each other, then for the Moon, Venus and Mercury e and α differ considerably. Distribution of the gravitational potential energy of a heavenly body or its gravitational potential is related to the degree of compression.

Mars is rotating around its own axis almost with the same period as that of Earth: the Martian days are 41 minutes longer than those of Earth (average solar days). And here, Venus and Mercury are /33
rotating extremely slowly and Venus in a direction opposite the direction of movement for the orbit. From the other planets, a similar feature is observed only on Uranus, whose axis of rotation lies almost in the plane of its orbit (see Figure 5). In the low planets -- Venus and Mercury, there is a shift in phase similar to the phases of the Moon with a period on the average of 584 Earth days for Venus and 116 days for Mercury (synodic period).

The problem of determining the periods of rotation of Venus and Mercury and their rotation around the Sun (incidentally, like a number of other characteristics of these planets) has a long history. This involves the fact that the surface of Venus in an optical range is not visible, but Mercury is very difficult to observe due to the smallness of its angle of dimensions (changing within limits from 13" to 5") and the small angles of distance from the Sun not exceeding 28°. In just the two last decades, we have obtained reliable values of these characteristics by radar study of planets.

Radar measurements of Venus were begun in 1961 simultaneously in the Soviet Union by a group of workers at the Institute of Radio

Engineering and Electronics of the Academy of Sciences USSR under the direction of V. A. Kotelnikov and in the USA by workers of the Massachusetts Institute of Technology and the California Technological Institute and in England at the Jodrell Bank Observatory. During these and subsequent experiments frequency and time spectra of the radio signal reflected from the planet were measured, the Doppler shift of its frequency, the intensity of reflected radiation and its depolarization and also the propagation time for the signal. On the basis of measurements of angular velocity and rotation of the planet which were made by several methods, elements of its rotation were determined.

A large series of experiments made it possible to obtain the value of the sidereal period of rotation of Venus which is considered to be, at the present time, by the International Astronomical Union: 243.0±0.1 earth days (e.d.). Later probing at a wavelength of 39 cm produced, obviously, a somewhat more precise value of 243.1 earth days. The data of many years of photographic and radar measurements of the parameters of rotation of Mercury led, respectively, to values of the period 58.644±0.009 earth days and 58.65±0.1 earth days. From an analysis of the phototelevised images of Mercury published in 1974 /34
by the Mariner-10 spacecraft, a period of 58.6461±0.005 earth days was obtained.

The gaseous shell of Jupiter, Saturn, Uranus and Neptune is inherent to differential rotation, that is, the change in the period of rotation with latitude which can involve dynamic processes in the atmosphere. On Jupiter, the tropical zone of the atmosphere is rotated more rapidly than the polar by 5 min 11 s, that is, the difference comprises about 1% and on Saturn it reaches almost 5%. For Jupiter, obviously it is the closest to the true value of the period corresponding to rotation of its magnetic field and determined by modulation of intensity and direction of polarization of intrinsic radio emission of the planet ($09^h55^m29.7^s \pm 0.07^s$). It is considered that it is best characterized by rotation of the more viscous regions of the planet lying below.

In 1977, S. Hayes and M. Belton, and after them a number of other scientists, put the values of the periods of Uranus and Neptune in some doubt; these values had been determined in 1912 by well-known astronomers P. Lowell and V. Slayfer and later by D. Moore and D. Menzel according to the slope of the Fraunhofer lines in the spectrum of reflection caused by rotation of the planet. These values comprised 10.8 hr for Uranus and 15.8 hr for Neptune. Hayes and Belton concluded that there were considerably larger values of the periods after having analyzed a large number of intrinsic spectral measurements at the Kitt Peak Observatory and having reconsidered once more the series of earlier observations.

The new values appeared close to twice those of the period of rotation determined earlier for these planets. Later on, however, an error was detected and the period of rotation of Neptune was decreased almost to its former value of 15.4±3 hr. Finally, observations made in 1983 using new high-sensitivity receivers of radiation (the so-

called PZS-detectors) made it possible to obtain, obviously, a more precise value for the optical period of Neptune in the middle latitudes: $17^h50^m \pm 5^m$. If we pay attention to the fact that the dynamics of atmospheric circulation on Neptune, probably, is similar to the dynamics of Jupiter and Saturn, then this value must be close to the period of rotation for the inner areas of the planet. As to Uranus, first of all on its disk one cannot successfully detect any kind of local irregularities and its period of rotation is estimated /35
still with indeterminancy: 24 ± 4 hr. These latter values are shown in Table 1. This does not exclude the fact that on the differences obtained not only do method difficulties for conducting such measurements have an effect but also the actually existing irregularity of rotation of the visible surface of the planet. Proposals have been brought out according to which the effect of differential rotation on Uranus and Neptune can prove to be even more significant than on Jupiter and Saturn.

Questions of determining the shapes of the planet and degrees of their difference from the state of hydrostatic equilibrium are closely related to problems of the inner structure and in more detail we will pause to discuss these questions later. While we only note that the most interesting feature of the shape is observed on Mars, which has a northern hemisphere (according to the lines of the large circle inclined at $\approx 35^\circ$ to the equator) that is more oblate than the southern hemisphere, that is, it differs more noticeably from a spheroid. The center of the figure is shifted relative to the center of mass by 2.5 km in a direction 98° W and 57° S. Venus has a lesser asymmetry in shape. According to the data of radar for wavelength 3.8 cm, the cross section of the planet in the equatorial plane is approximated by an ellipse whose difference in half-axis comprises 1.1 ± 0.4 km (for a comparison let us indicate that for Earth this difference is <0.2 km) and the center of the figure is shifted relative to the center of mass by 1.5 ± 0.3 km in the direction to Earth in the epoch of a lower conjunction.

Due to the spheroidal shape of the planets caused by rotation, their axis of rotation does not retain its position in space but under the effect of gravitation perturbations undergoes periodic oscillations. Here the well-known precession and nutation oscillations of the Earth's axis are involved imparting to the Moon and the Sun an equatorial band of Earth's spheroid inclined toward the plane of Earth's orbit or ecliptics at an angle of 23.5°. The resulting moment of force created strives to turn the equatorial plane in such a way that it matches the plane of the ecliptics and then the gravitational effect of the Sun is approximately 2.2 times smaller than that of the Moon due to its great distance -- almost 400 times. Inasmuch as the Earth has a large mass and is similar to a gyroscope, it rapidly rotates and such a turn does not occur but orientation of the axis of rotation (and this means the axis of the world) in space /36
changes periodically: it describes around the axis of the ecliptics a surface of a cone with an angle of solution 23.5° (precesses) like the axis of a gyroscope. Respectively, the North and South Poles of the world describe the circle on the heavenly sphere. This precession movement occurs clockwise from east to west (that is, on the side

opposite the annual movement of the Sun on the heavenly sphere), at a velocity of 50.3" per year. Therefore, the full rotation around the axis of the ecliptic occurs for $\frac{360^\circ}{50.3''} \approx 25800$ years -- is the period of precession of the Earth's axis.

It is necessary to add to this that inasmuch as the plane of the lunar orbit is inclined toward the plane of ecliptics on the average at an angle of $5^\circ 09'$, it itself precesses around the axis of ecliptics with a period of about 19 years -- this is the so-called regression of the plane of the lunar orbit. Moreover, when the Sun (in March and September) and the Moon twice a month intersects the heavenly equator, their dynamic action on the equatorial band of the Earth's spheroid does not create a moment striving to incline the axis of rotation. Altogether, all of these effects lead to a small additional oscillation (nutation) of the Earth's axis. Therefore, the poles of the world at the same time describe around the poles of the ecliptics circles modulated by the frequency of nutation oscillations.

The most characteristic result of precession is a change in the position of stars on the heavenly sphere in the equatorial system of coordinates. Thus, for example, at the present time, the North Pole of the world approaches the Polar Star. Angular distance between them comprises right now 50' and in 2103 years decreases to a minimum value of 27'. However, even in 3000 years, it increases to $\approx 5^\circ$ and by 4200 years the North Pole of the world will be $\approx 2^\circ$ from α Cepheus. Finally, 13,800 years closer to the North Pole of the world, the bright star (at a distance of $\approx 5^\circ$) is Vega (α Lyra). Such a shift will be repeated with a period of about 26,000 years but, of course, the angular distances of these stars from the poles of the world will be somewhat different.

Precession and nutation are the most characteristic and best studied forms of movement of the Earth's axis. It is proposed also that there are other long-period oscillations as a result of the gravitation perturbations, leading to a change in inclination of the axis of rotation in space. According to the calculations of Soviet scientists Sh. G. Sharaf and N. A. Budnikova, for the last 30 million years, the inclination of the axis of rotation of Earth has changed /37 approximately from 22.1° to 24.6° with a period of about 40 and 200 thousand years.

The massive Moon satellite has a strong stabilizing effect on the position of the axis of rotation of Earth. Mars has no similar satellite and therefore its axis of rotation probably undergoes stronger oscillations relative to the plane of ecliptics. As calculations of the American scientist V. Ward have shown, they can be due to application of three effects: change in the inclination of the plane of the orbit to the plane of elliptics and the equator to the plane of the orbit as a result of gravitation perturbations of the planet-giant and precession of the axis of rotation itself caused by the effect of moment from the Sun on the asymmetrical shape of the planet. As a result, the position of the axis of rotation in space varies with a period of 120,000 years (period of precession) and the amplitude of oscillation changes with a period of 1.2 million years as is shown in Figure 6. Then, the inclination of the equator i changes from 14.9° to 35.5° and the modern value of 25.2° presented in Table 1 must be considered as an intermediate value.

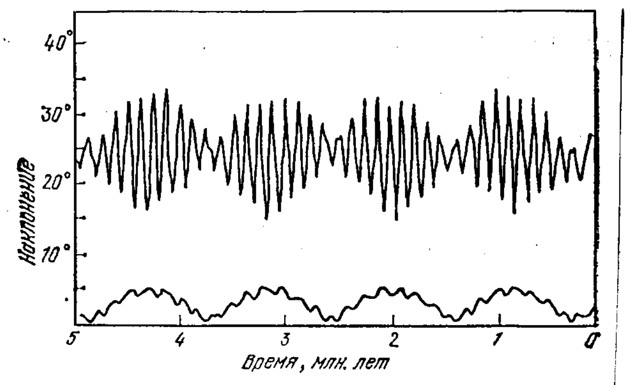


Figure 6. Variation of inclination of the equator of Mars to the plane of its orbit taking into consideration precession of the axis of rotation (upper curve) and variation in inclination of the plane of the Martian orbit to the ecliptics (lower curve) for the past 5 million years. The present value is 25.2°.
Key: a. inclination; b. time, million years.

Properties of the Orbit

The characteristics of movement of the planets determine the entire set of dynamic properties in the solar system. The rotation of the planets around the Sun is subject to Kepler's laws which make it possible to approximately determine the position of the planet on a non-perturbed orbit /38 at any moment of time. In order to transfer from the position closest to a more precise definition (ephemeris of the planet), it is necessary to take into consideration perturbations in motion. These perturbations leading to deviation from the calculated elliptical trajectory (Kepler ellipse) occur as a result of mutual attraction of planets, depending on their position relative to each other and periodically changing with the passage of time. Additional perturbation is detected in the movement of Mercury for which, due to the closeness of the Sun, one must introduce a correction for the shift of the perihelion by 42" in a century; this comes from the general theory of relativity. It is impossible, truly, to exclude the fact that the agreement of these observations with the value of this effect was theoretically predicted by A. Einstein within the limits of error of measurement (≈1%) caused, to an equal degree, by the effect of the quadrapole moment of the Sun, taking into consideration in a first approximation, the difference in the external gravitational potential of the Sun from the Newtonian potential for an ideal sphere.

The elements of orbit undergo a long-period perturbation whose character is determined by analytical solutions of the equations of movement and the theories well known in classical celestial mechanics. They, in particular, include the idea that inasmuch as movement is almost completely determined by gravitational forces (or, in other words, a system in which perturbation movement of the celestial body occurs, is conservative in distinction, for example, from the case of an artificial satellite on which the resistance of the gas of the upper atmosphere already has an effect), the large half-axes and, consequently, the periods of rotation of planets around the Sun remain unchanged. As to the eccentricities and inclinations, for the upper planets at the limits of their changes, strong limitations are applied which come from the conditions involving these elements with other characteristics of orbital movement.

Certain properties of orbital and rotational movement are evidence of the existence of a number of principles which are a result of the general distribution of mass in the dynamic system of planets and satellites. With total mass of the planets comprising in all 1/750 of the mass of the Sun, on them about 98% of the total moment of the quantity of motion of the solar system is involved. The planet /39
satellites make an insignificant contribution to this value. All of the planets move in a direction coinciding with rotation of the Sun, their orbits have a small inclination toward the plane of the solar equator and small eccentricities (except for Mercury and particularly, Pluto; see Table 1).

The presence of even comparatively small elliptical position of the orbit causes noticeable seasonal changes, due to the large flow of energy from the Sun (insolation) in the perihelion. For Mars, the axis amounts to about 45% and for Mercury it reaches 200%. However, the main role in seasonal changes is played by inclination of the axis of rotation from the normal toward the plane of the orbit. For Venus, for example, eccentricity and inclination is close to 0 and shift in seasons does not occur; at the same time, for Mars, both factors play a role leading to, besides a clearly expressed seasonal progress, a different duration of seasons in the northern and southern hemispheres.

The principle which we know by the name of the Titius-Bode rules named after the law of planetary distances is noted in the position of the planets. According to this law, the ratios of the large half-axes of a sequential series of planets, the farther they get from the Sun ($n = -\infty$ for Mercury, $n = 0$ for Venus, $n = 1$ for Earth, etc.) are almost constant so that $a = 0.1 \cdot (3 \cdot 2^n + 4)$ IAU. This relationship produces, with a value of $n = 3$, the position of the band of asteroids, obviously, a relict of the stage of accretion in the form of an unshaped planet. At another time, the opposite point of view was held: certain scientists consider that this was a fragment of a planet which existed at some time which was named Phaethon. This hypothesis was brought out for the first time by the German astronomer

G. Olbers in 1804 soon after the discovery by him of a second small planet -- Palladia. Olbers' hypothesis was greeted with enthusiasm by his contemporaries inasmuch as it made it possible to rehabilitate the law of planetary distances. However, later on, with an increase in the number of asteroids discovered, it became more and more obvious that the multiplicity of their orbits could not be explained by the destruction of one large planet and the hypothesis of crushing of many comparatively large bodies was more accurate. Therefore, at the present time, the hypothesis about the planet Phaethon essentially has been repudiated. At large distances from the Sun, the law of planetary distances holds up poorly: a noticeable deviation is detected from this law /40
for Neptune and it is completely unusable for Pluto.

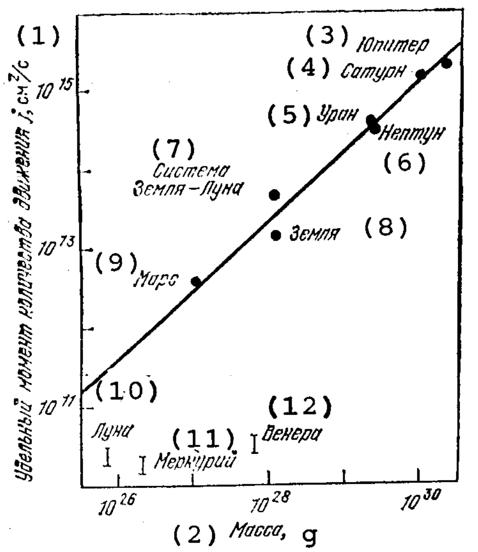


Figure 7. Distribution of specific moment of the quantity of motion of planets depending on their mass.
Key: 1. specific moment of the quantity of movement j, cm^2/s;
2. mass, g; 3. Jupiter;
4. Saturn; 5. Uranus;
6. Neptune; 7. Earth-Moon system; 8. Earth;
9. Mars; 10. Moon;
11. Mercury; 12. Venus.

A characteristic feature is distribution of the specific orbital moment in the planetary system. It is not difficult to confirm here that it increases proportionally to the root of the square of the radius of the orbit r, that is, $J \approx r^{1/2}$, inasmuch as $J = vr$ and the circular velocity $v = \left(\frac{Gm}{r}\right)^{1/2}$, where G is a gravitational constant.

Another interesting feature is the positive correlation observed between the velocity of rotation of the planet and its mass m, that is, the larger the mass, the greater is the velocity of rotation. The specific rotational moment (moment of the quantity of movement per unit of mass) is expressed in the form $j = \frac{C}{m}$, where C is the moment of inertia relative to the axis of rotation. The relationship between j and m shown graphically in Figure 7 corresponds to the graduated relationship $j \approx m^{5/6}$.

An exception here is Venus and Mercury which, obviously, to the greatest degree are affected by the tidal friction from the Sun. As /41
to the Moon, from the point of view of dynamics, one must not consider the Moon and Earth separately, but as a system of Earth-Moon for which the appropriate correlation between moment and mass appears to be fairly good.

In the parameters of movement of planets and their satellites, there are a number of interesting relationships maintained as a result of the presence of a commensurate nature and resonances. The fact that the Moon has one side constantly turned toward Earth is a characteristic example of resonance 1:1 between the periods of rotation according to orbit and rotation around the axis. Other examples are synchronization of the periods of rotation and revolution of Mercury (in resonance 3:2), synchronization of rotation of Venus relative to Earth, the commensurate nature in orbital movement of Pluto and Neptune, Jupiter and Saturn, the three Galilean satellites of Jupiter and the four satellites of Uranus, etc. Synchronization of rotation of heavenly bodies with their orbital movement is described well by the laws of D. Cassini. They were established by this notable French astronomer empirically for rotation of the Moon even by the middle of the eighteenth century and later were generalized for a broader spectrum of movement. The commensurate nature is more precisely apparent in the so-called average movements -- parameter n involving the force of gravity of the central body which has a mass m with large half-axis of the orbit a:

$$n = \sqrt{Gm/a^3}$$

Another parameter which is widely used in celestial mechanics is directly involved with it -- the average anomaly $M = n(t - t_p)$ where the second factor is the difference of moments of time of passage of the planet (or satellite) of a certain current point of orbit and pericenter.

As was apparent, there are dozens of pairs of bodies for which the ratio of average movement hardly differs at all from whole numbers and are included in certain limits (primarily less than 7). This circumstance, of course, cannot be explained by a simple coincidence or randomness. Such a principle is apparent in relation to the average anomalies among Io, Europa and Ganymede and between the average anomalies and rates of rotation of Mercury and Venus, in the presence of a commensurate nature between average movement of Jupiter and Saturn as a result of which the relative mutual positioning of /42
these planets is repeated with a period of 14,400 years. The commensurate nature existing in the movement of Neptune and Pluto explains another interesting property: these planets cannot approach each other at a distance of less than 18 IAU in spite of the fact that in the perihelion of Pluto, it approaches the Sun closer than does Neptune (see Figure 5). Interesting dynamic principles are characteristic for the orbits of the asteroids. In the majority of them, one finds the commensurate nature of average movement with the average movement of Jupiter not far from which is located the main quantity of these celestial bodies. Then it seemed that the asteroids are distributed by groups with approximately identical average movement (and this means large half-axes of orbit are hardly different). In a space from 2.17 to 3.64 IAU filled with the asteroid band, several fields are detected in which there are practically no asteroids, that is, these fields appear to be "forbidden." They have been called the Kirkwood holes; in these, the periods of rotation are

TABLE 2. BASIC CHARACTERISTICS OF THE PLANET SATELLITES

Planet	Satellites	Average radius, km *)	Mass (in mass of planet)	Density, g/cm^3	Albedo	Orbit radius in planet radii	Orbit radius in 10^3 km	Period of rotation (Earth days)	Orbit eccentricity	Inclination to equator of planet, degr.
Earth	Moon	1738	$1,23\cdot10^{-2}$	3,33	0,07	60,27	384,4	27,32	0,055	5,09
Mars	Phobos	13,5	$1,82\cdot10^{-8}$	2,1	0,06	2,76	9,4	0,319	0,015	1,02
	Deimos	7,5	$2,14\cdot10^{-9}$	2,1	0,07	6,92	23,5	1,262	0,001	1,82
Jupiter	XIV Adrastea	20	$\sim3\cdot10^{-11}$		<0,10	1,80	128	0,295	~0,0	~0,0
	XVI Metis	20	$\sim3\cdot10^{-11}$		<0,10	1,80	128	0,295	0,0	~0,0
	V Amalthea	135	$\sim10^{-8}$		0,05	2,55	181	0,489	0,003	0,4
	XV Phiva	40	$\sim3\cdot10^{-10}$		<0,10	3,11	221	0,675	~0,0	~0,0
	I Io	1815	$4,70\cdot10^{-5}$	3,53	0,62	5,95	421	1,769	0,004	0,0
	II Europa	1569	$2,57\cdot10^{-5}$	3,03	0,68	9,47	670	3,551	0,000	0,5
	III Ganymede	2631	$7,84\cdot10^{-5}$	1,93	0,44	15,1	1070	7,155	0,001	0,2
	IV Callisto	2400	$5,60\cdot10^{-5}$	1,83	0,19	26,6	1880	16,689	0,010	0,2
	XIII Leda	5	$\sim5\cdot10^{-13}$			156	11 110	240	0,146	26,7
	VI Himalia	90	$\sim3\cdot10^{-9}$		0,03	161	11 470	250,6	0,158	27,6
	X Lysithea	~10	$\sim4\cdot10^{-12}$			164	11 710	260	0,130	29,0
	VII Elara	40	$\sim3\cdot10^{-10}$		0,03	165	11 740	260,1	0,207	24,8
	XII Ananke	~10	$\sim4\cdot10^{-12}$			291	20 700	—617	0,17	147
	XI Carme	~15	$\sim10^{-11}$			314	22 350	—692	0,21	164
	VIII Pasiphae	~20	$\sim3\cdot10^{-11}$			327	23 300	—735	0,38	145
	IX Sinope	~15	$\sim10^{-11}$			333	23 700	—758	0,28	153
Saturn	XVII Atlas (1980 S28)	20			0,4	228	137,7	0,602	0,002	0,3
	XVI Pandora (1980 S27)	70			0,6	2,31	139,4	0,613	0,004	0,0
	XV Prometheus (1980 S26)	55			0,6	2,35	141,7	0,629	0,004	1,1
	X Epymethius (1980 S3)	70			0,4	2,51	151,4	0,695	0,009	0,3
	XI Janus (1980 S1)	110			0,4	2,51	151,5	0,695	0,007	0,1
	Mimas	196	$6,50\cdot10^{-8}$	1,4	0,7	3,08	185,5	0,942	0,020	1,5
	I Enceladus	250	$1,48\cdot10^{-7}$	1,2	1,0	3,95	238,0	1,370	0,004	0,0
	II Tephiya	530	$1,09\cdot10^{-6}$	1,2	0,8	4,88	294,7	1,888	0,000	1,1
	XIII Telesto (1980 S13)	17			0,6	4,88	294,7	1,888		
	XIV Calypso (1980 S25)	17			0,8					
	IV Dione	560	$2,04\cdot10^{-6}$	1,4	0,5	6,26	377,4	2,737	0,002	0,0
	XII 1980 S6	18				6,27	378,1	2,739	0,005	0,2
	V Rhea	765		1,3	0,6	8,74	527,1	4,518	0,001	0,4
	VI Titan	2575	$2,46\cdot10^{-4}$	1,9	0,2	20,25	1221,9	15,95	0,029	0,3
	VII Hyperion	205			0,3	24,55	1481,0	21,28	0,104	0,4
	VIII Iapetus	730		1,2	0,50/0,05	59,02	3560,8	79,33	0,028	14,7
	IX Phoebe	110			0,06	214,7	12 954,0	—550,4	0,163	150
Uranus	V Miranda	120	$1,0\cdot10^{-7}$			5,49	129,2	1,460	0,010	0,0
	I Ariel	565	$1,1\cdot10^{-5}$		0,30	8,08	190,1	2,555	0,003	0,0
	II Umbriel	555	$1,1\cdot10^{-5}$		0,19	11,25	264,7	4,015	0,004	0,0
	III Titania	800	$3,2\cdot10^{-5}$		0,23	18,46	434,3	8,760	0,002	0,0
	IV Oberon	815	$3,4\cdot10^{-5}$		0,18	24,69	580,8	13,51	0,001	0,0
Neptune	I Triton	1600	$2,2\cdot10^{-4}$			15,85	394,7	—5,840	0,000	2,79
	II Nereida	100	$5,0\cdot10^{-8}$			249,5	6212	358,4	0,756	0,48
Pluto	Charon	560	$6,4\cdot10^{-2}$	0,7—1,2	0,4	12,15	17	6,4		

*) For satellites with irregular shape, half of the maximum dimensions is indicated.

short and the period of rotation of Jupiter and bodies setting behind it undergo maximum tidal perturbation. Similar principles are apparent in the structure of Saturn's rings, which we will discuss in more detail in a later section of Chapter III.

Earth and all of the upper planets have satellites whose names and basic characteristics are presented in Table 2. From the point of view of cosmogony, the greatest interest exists in the fact of the undoubted similarity of satellite systems of planet-giants with the same planetary system -- Jupiter's system, for example, can be compared with the solar system. Actually, the ratio of total mass of satellites to mass of planets corresponds in magnitude to the ratio of the mass of the planets to the mass of the Sun ($\approx 10^{-3}$), and the orbits of the majority of satellites also have small eccentricities and inclinations; and for their relative position we will use the law of planetary distances. One should particularly emphasize the study of the planet-satellite system is extremely important for problems of long-term evolution of a celestial body, particularly in the case of interaction involving exchange of energy. Besides the synchronous rotation of Earth relative to Moon at resonance 1:1, similar features of synchronization (when the rate of rotation is equal to average movement n in orbit) is detected in the movement of satellites of Mars -- Phobos and Deimos, the Galilean satellites of Jupiter. Obviously, they are also characteristic for other satellites of planets, which /45
are, in this way, one more remarkable property of movement in the solar system.[1]

Tidal Interactions

The most accurate explanation of synchronization, smallness of eccentricities and inclination of orbits and also the existence of commensurability in the middle movements of the planets and satellites, at the present time, is obtained starting from the mechanism of tidal friction. As the basis of this mechanism, we have the concept of dissipation of energy of gravitation perturbations in celestial bodies inasmuch as these bodies do not have ideal elasticity. As the simplest measures of inclination from the ideal elasticity, we use the so-called dissipative function 1/Q, characterizing damping of any oscillation process and defined as the portion of mechanical energy which is scattered per oscillation cycle. The value of Q called the energy or Q factor is used to measure the quality (resonance properties) of the oscillation system and is broadly used, for example, in radio engineering for characteristics of oscillatory circuits. For a contour with inductance L, capacity C, ohmic resistance R: $Q = \frac{1}{R}\sqrt{\frac{L}{C}}$, or $1/\omega^{1/2}RC$, where ω is the intrinsic frequency of the circuit. As we see, Q indirectly depends on frequency although for actual mountain rock, whose properties are determined by the "mechanical Q factor" of the system, this dependence is not very strongly apparent. The value of the Q factor is characterized also as

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[1]Table 2 does not include recently discovered new satellites for the planet Uranus.

selective properties of the oscillatory system: the larger the value of Q, the narrower is the band of frequency of external force capable of causing oscillation. Essentially, the Q factor is defined as how many times the amplitude of the established forced oscillations during resonance exceed the amplitude of forced oscillation at frequencies not coinciding with the inherent frequency system. Physical nature of dissipation in planetary bodies obviously involves, mainly, the forces of viscous friction and the breakdown of the ideal structure of crystal lattices (admixtures, dislocations, non-ordering, etc.). For Earth, for example, the value of Q is minimum in relation to the boundary of the lithosphere with the asthenosphere lying at a depth /46
between 50 and 100 km where it comprises $Q \approx 100$ (such a magnitude of Q as on a radio circuit). With the farthest increase in depth, the Q factor rapidly increases, becoming practically constant in the low mantle.

The rigid upper limit for the value of the dissipative function for planets is applied as the position of orbit of these satellites. The period of rotation of the overwhelming majority of satellites is larger than the period of rotation of the planets; an exception is for the satellite of Mars, Phobos, and satellites of Jupiter, Adrastea and Metis. Obviously, the greater, the dissipation, the farther removed the orbit must be to intersect the satellite (as has obviously occurred with the Moon). Actually, in the field of the gravitational potential, transmission of the moment of quantity of motion of the planet to the satellite must be equalized by the moment of rotation caused by the effect of the satellite on the planet. If the tidal reaction of the planet on the satellite were instantaneous, then the full moment of rotation would be equal to zero inasmuch as the tidal bulge would always be symmetrical relative to the line of the planet and satellite. Moreover, as is shown in Figure 8, as a result of non-absolute elasticity and dissipation of energy, a phase shift δ will occur. Because $\omega_{pl} > \omega_{sat}$, the maximum tidal bulge on the planet is away from the planet-satellite line. The satellite creates a counteracting moment, striving to slow down rotation of the planet. At the same time, the effect of the bulge on the satellite creates a moment of rotation equal in value and opposite direction causing an increase in energy and moment of the quantity of motion of the satellite. The result of this must be an increase in the large half-axis of the orbit of the satellite and a slowdown in velocity of its motion.

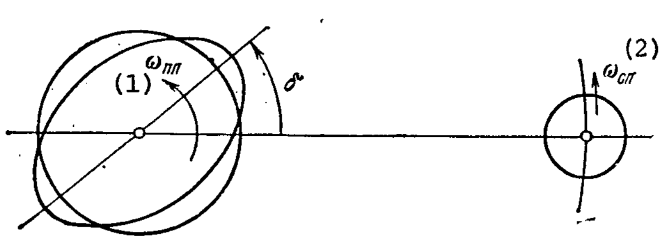

Figure 8. Diagram of the formation of a tidal hillock and its time lag during movement of the satellite. Key: 1. pl [planet]; 2. sat [satellite].

The energy of rotation lost by the Earth comprises a fairly /47
impressive value of $2.8 \cdot 10^{19}$ erg/s (for comparison, let us mention that Earth receives from the Sun $1.7 \cdot 10^{24}$ erg/s, the power of the

atmospheric circulation is estimated as approximately $2.4 \cdot 10^{22}$ erg/s, energy generation at the moment of powerful magnetic storms and polar auroras comprises about 10^{19} erg/s, and the power of the largest modern electric power plants is $<10^{17}$ erg/s).

Calculations show that the main part of slowdown of rotation of Earth comprising about 3.5 ms per hundred years, is caused by ocean tides (at the same time the slowdown is less, inasmuch as at the same time acceleration of rotation occurs by approximately 1.5 ms per one hundred years; its cause is still not clear). A significant portion of energy, obviously, is also dissipated due to the solid-body friction between separate blocks in the crust and mantle of Earth.

According to the measurements of Earth tides, it is found that slowing down rotation of Earth due to tidal friction corresponds to a value of $Q \approx 15$. Inasmuch as the rate of dissipation of energy is defined as the average rate of work produced by the Moon on Earth and consequently, by Earth on the Moon for an oscillatory cycle, it is possible to obtain an estimate of the effect of tidal friction on evolution of the lunar orbit. Then it seems that due to increments of energy of motion, a large half-axis of the lunar orbit is increased by approximately 3 cm/year, simultaneously insignificantly the eccentricity and inclination of it change. Now, if it is assumed that the tidal characteristic which is measured by the function Q was retained during ancient geological eras in the history of Earth (at least for the Archean to Aphebian eras) as unchanged, it would be possible to counter the concept that about 1.5 billion years ago the Moon was located close to Earth and its orbit had a noticeably greater inclination toward the plane of the Earth's orbit (and Earth days at that period were almost five hours shorter). Inasmuch as, however, the results of analysis of lunar soil firmly prove the significantly more ancient age, obviously, the corresponding age of Earth (4, 6 billion years), hypotheses about the comparatively "recent" formation of the Moon are excluded. Also, the hypothesis about "mooring" of the Moon to the Earth about 1.5 billion years ago appears hardly probable; therefore, most probably, one can assume that earlier the Earth-Moon system (formed as part of a single process) had a significantly smaller tidal dissipation in comparison with the modern epoch. /48

Thus, under the effect of tidal friction in a rotating planet, an increase must occur in the large half-axes of the orbit of its satellites which gradually move farther away from the planet. Due to gravitation interaction, the moment of quantity of motion is transmitted from one satellite to another and their period of rotation becomes mutually related and commensurability of middle movement occurs. Taking into consideration the relatively close positioning to its planet of the Jupiter satellites and other satellites of the planet-giants, evidencing weaker dissipation than for Earth, the lower limits of the Q factor are estimated for them at a value of $\approx 10^4$ (a tuning fork has such a magnitude for its Q factor). Experimental confirmation of the important role of the mechanism of tidal friction comparatively recently was obtained for the Galilean satellites of Jupiter. Phenomenal effects caused by tidal dissipation were detected, primarily on Io, which we will become more familiar with in Chapter III.

The mechanism of synchronization relative to the axis of rotation of the satellite of the planet or the planet itself has a similar nature; this synchronization results in coincidence (or commensurability) of the average velocity of rotation with average motion n. The decrease in angular velocity occurs in this case under the effect of the righting moment having an effect on the tidal bulge of the satellite. The righting moment is proportional to the ratio of difference of equatorial moments of inertia A and B to the polar C. In a general case, when the satellite is in an elliptical orbit with noticeable eccentricity, the moment of rotation created by gravitation of its tidal bulge by the planet strives to approach the velocity of rotation of the satellite for an angular velocity at the pericenter. As rotation slows, the lag time of the bulge along the orbit decreases and, respectively, transmission of the moment of the quantity of motion. At the limit, when the angular velocity of rotation and movement in orbit are practically equalized, there is no transition of moment and only an exchange of tidal energies occurs. It is of some interest to note that according to an estimate by American scientist S. Peale, the time required for tidal lag of a nonsynchronous rotation and synchronization of it with orbital motion for a satellite of the Amalthea type, in the gravitational field of Jupiter, comprises no more than 10^4 years.

Now we turn again to the question of rotation of the two lower /49
planets -- Venus and Mercury. We have already talked about the fact that a considerable amount of time and effort is needed primarily with high precision which will, in the end, determine their completely unusual periods of rotation. However, their unusual aspect includes more than the fact that both these planets rotate extremely slowly. The values obtained are of great interest from the point of view of the manifestation of the principles again caused by the mechanism of tidal friction.

The period of rotation of Venus appeared to be very close to the period of resonance of rotation of the planet relative to Earth which equals 243.16 days. Then, in each of the lower ($\phi = 180^\circ$) and upper ($\phi = 0^\circ$) conjunctions, Venus turns the same side toward Earth. With the reverse direction of rotation, this corresponds to duration of solar days on Venus of 116.8 Earth days, that is, the Venusian year comprises approximately two Venusian solar days.

Resonance rotation of Venus relative to Earth, obviously, is caused by the effect of gravitational pull of Earth on the nonsymmetrical figure of Venus. However, for stability in the state of resonancy, it is necessary that the stabilizing moment of Earth $T_{\oplus}$ was greater than the tidal moment of Venus in the gravitational field of the Sun $T_{\odot}$. This means that the asymmetry found for the shape of Venus must be adequate for guaranteeing the difference in moments of inertia relative to the equatorial axes A and B necessary for completing the condition $T_{\oplus} > T_{\odot}$. Moreover, the relative width of the resonance zone on Venus appears to be extremely small, considerably smaller than for the Moon or Mercury. Starting from the generalized Cassini laws, V. V. Beletskiy and S. I. Trushin pointed out that for retaining movement in the limits of the resonant zone in the presence of periodic solar perturbations, it is necessary to fulfill the condition $\frac{B - A}{C} \lesssim 2.5 \cdot 10^{-5}$. An analogous ratio for the Moon has a magnitude of $\approx 5 \cdot 10^{-4}$ from which it follows that this condition is very critical and the phenomenon of resonance rotation of Venus which it is called lies "on the limit of the possible."

An additional factor facilitating synchronization of rotation of Venus by Earth can be atmospheric tides. Moreover, the American scientists T. Gold and S. Soter have also turned their attention to the possible role of 24-hour variations in pressure and powerful /50 atmosphere of Venus due to heating by the Sun. Actually, the minimum pressure and mass occur in the post-meridional field of atmosphere and the maximum on the pre-meridional. This distribution of mass creates, in the gravitational field of the Sun, a moment $T'_{\odot}$, proportional to the period of rotation of the planet and opposite in sign the moment $T_{\odot}$, that is, accelerating its rotation. This decreases the effect of the slowing tidal moment of the Sun and makes synchronization of Venus to Earth easier. The precise condition of synchronization acquires, in this case, the form $T_{\oplus} > T_{\odot} - T'_{\odot}$.

The hypothesis about synchronous rotation of Mercury, that is, about the equality of periods of its rotation and revolution, was put forward back at the end of the last century by the well-known Italian astronomer D. Schiaparelli about observations of the absence of the visible mixing of separate spots on the disk of the planet relative to the terminator and confirmed by a number of later investigations up to the middle of the 1960's. The precise value found for the period of rotation does not contradict the confirmation about synchronous rotation inasmuch as a period of about 88 days is not unique. G. Colombo was the first to direct his attention to the circumstance that in the case of a non-isotropic moment of inertia, the planets can have a stable regime and then the period of rotation comprises 2/3 of the orbital period or 586,461 Earth days. This interesting variation of resonance, the so-called resonance with spin oscillations, in which due to tidal interaction of the planet with the Sun, there could have been a transfer of its angular moment and, respectively, a decrease in the rate of rotation and "capture" in the existing resonance regime. A detailed theoretical consideration of this interesting effect was made in the works of the American scientists G. Colombo and I. Shapiro, P. Goldreich and S. Peale and the Soviet scientist V. V. Beletskiy.

It is important to emphasize that for the occurrence on Mercury of a spin-orbital resonance 3:2 one requires very insignificant compression of the ellipsoid of inertia in the plane of the equator, on the order of $(B-A)/C > 10^{-5}$. Deviation from the strictly concentrated distribution of mass close to this plane, possibly, is due to gravitational anomalies similar to the region on the Moon with /51 increased concentration of mass. These are called mascons. The largest of the hypothetical mascons of Mercury is associated with a tremendous (cross section 1300 km) Caloris Basin (also called the Sea of Fires) always turned toward the Sun in the perihelion of the orbit.

The duration of solar days on Mercury determined by the combined effect of rotation and revolution in orbit appears to be equal to three stellar Mercury days or two Mercury years and comprises 17,594 Earth days. It is interesting that due to the large eccentricity of orbit of Mercury, the daily movement of the Sun in the sky of this planet is not uniform. It moves more slowly when the planet is found in the aphelion. In the perihelion, where the angular velocity of orbital movement of the planet exceeds the velocity of its rotation, the daily movement of the Sun (in general occurring from east to west) in a comparatively short period of time becomes fivefold. This unusual phenomenon continues for approximately 8 Earth days.

Comparatively recently, American researchers T. van Flendern and R. Harrington have attempted to find an explanation for several unusual orbits of Mercury and its quasiresonance rotation within the framework of the hypotheses put forward earlier, according to which Mercury at some time was a satellite of Venus, similar to the Moon for Earth. According to the results of modeling on a computer, the authors have concluded that the situation is possible in which Mercury found in primary orbit with average distance ≈460,000 km from Venus must, due to tidal interaction, have had its intrinsic rotation gradually slowed down and simultaneously the rotation of Venus brought up to the inverse. In this dynamic model of Mercury, over a period of several millions of years, one could leave Venus going to the heliocentric orbit from its gravitational field through one of the Lagrange points lying on a straight line connecting both centers of mass inasmuch as the position of the body at these points is unstable (see Figure 3).

There is one more interesting idea also considered by numerical modeling on a computer by Harrington and van Flendern related to the attempt to explain the orbit of Pluto and its satellite Charon. Back in the 1930's, a proposal was put forward that Pluto is an "escaped" satellite of Neptune which was the result of its close approach to another satellite Neptune, Triton and therefore the movement of the latter changed in opposition. The famous American astronomer /52
D. Koyper, having confirmed that the concept of its independent formation as a planet is not compatible with the existing parameters of orbit -- great eccentricity and inclination considered that Pluto was a satellite of the proto-Neptune having left it after completion of the formation of the planet itself. Harrington and van Flendern considered several other models according to which the escape took place as a result of perturbation which was confirmed by a system of satellites of Neptune from an unknown planet with mass on the order of 10 masses of Earth. With passage close to Pluto, the planet must have itself undergone strong perturbation which would throw it to a distance of approximately 50-100 IAU from the Sun where it, possibly, is found right now. Theoretically, this situation is possible and

quantitatively its basic realism with the indicated hypotheses is confirmed by calculations. However, there is no more weighted basis in favor of this interesting idea, primarily, because there are no data about the existence of a tenth planet in the solar system beyond the orbit of Pluto. We are talking about "as before," inasmuch as a similar hypothesis was put forward about 20 years earlier starting from the fact of systematically recorded divergencies in the movement of Uranus and Neptune predicted in theory and obtained from observations. If such a planet, as was proposed, has a mass approximately equal to the mass of Jupiter and was a distance of 60 IAU from the Sun, then it would be observed as an object with no less than a fourteenth stellar magnitude. Nevertheless, the regular searches with the possibility of discovering even significantly weaker objects did not produce any kind of results. Moreover, it is impossible to exclude the fact that this hypothetical near-Pluto planet X possesses a very low reflective capability (albedo) being even farther distant from the Sun and is found in an even more unusual orbit than the orbit proposed with an inclination on the order of 120°.

Certain Cosmogonous Results

The principles in the system of planets and satellites considered by us very definitely indicate a single process for their formation and makes it possible to put together several concepts of the most /53
probable means and mechanisms of this process. Modern cosmogonous theories including two cardinal problems -- the origin of protoplanetary nebulae and the formation of planets, -- rest both on the mechanical characteristics of bodies of the solar system and on new experimental data about the properties of surfaces and the composition of matter of planets and a comparison with samples of material of their origin -- the meteorites. Also, the successfully developed theoretical methods of modeling processes in radiated gas and cosmic plasma play an important role and, of course, the total great success of astrophysics and stellar cosmogony.

One of the first serious attempts to explain the basic principles of the origin of the solar system was undertaken by the important Soviet geophysicist O. Yu. Shmidt within the framework of his cosmogonous theory; at the same time, the German scientist K. Weizsacker was energetically developing this in the 1940's. In these theories, there was a significant difference from those put forward in the middle of the seventeenth century by the French thinker R. Descartes and in the second half of the eighteenth century by the German philosopher I. Kant and the French mathematician P. Laplace with concepts about the formation of planets from protoplanetary dust matter and from gaseous nebulae. These hypotheses are often called nebular from the Latin word nebula.

O. Yu. Shmidt considered the movement of all the planets in a single direction on a circular orbit lying approximately in a single plane as the result of a natural statistical averaging of the moment of quantity of motion of many cold bodies and particles, from whose combination the planets arose. Their subsequent geological evolution

was considered then as the result of separation of radiogenic heat from the interior. The law of planetary distance was obtained on the basis of primary distribution of mass of primary matter at the same time that Weizsacker defined the scale of turbulence in a gaseous disk with mass ≈0.1 mass of the proto-Sun. Both series did not permit, however, explaining the distribution observed at the moment of quantity of motion in the solar system without involving an artificial hypothesis about the capture by the Sun of interstellar dust clouds (protoplanetary nebulae) which already possess the necessary moment. Although such a capture, in principle, is possible, its probability is /54
low which was a vulnerable spot for this theory.

Striving to get around this difficulty, the English astrophysicist F. Hoyle put forward a hypothesis on the mechanism of transmission of the solar moment of the pulse of two planets at the stage of their formation during interaction caused by a strong magnetic field of the proto-Sun. Such magnetic adhesion simultaneously must slow down the rotation of the Sun and redistribution of the moment throughout the entire radius of the protoplanetary disk was proposed due to turbulent friction. However, then different perturbations in the plasma were not taken into consideration which would break down the indicated character of interaction. Therefore, the practical accomplishment of this mechanism also was somewhat doubtful.

In Hoyle's works, his own expression of the concept of simultaneous formation of the Sun and a protoplanetary cloud and the idea of the so-called instability were found; later on this was intensively developed by the well-known American cosmogonist A. Cameron and the French astronomer E. Shatsman. The basis of this is the process of separation of the Sun from the primary cluster of interstellar matter which has a large moment of quantity of motion as a result of the collapse of the central cluster due to the occurrence of instability. The formation of planets occurs as a result of decay of a thin rotating disk separated from this cluster by the effect of centrifugal force. Cameron proposes that the primary mass of a protoplanetary nebula must be on the order of the solar and separation of matter began at a distance approximately twice exceeding the radius of orbit of Pluto. Shatsman had both values approximately two magnitudes smaller, that is, the Sun generated in the beginning possessed a comparatively small mass and separation of the nebula occurred in the region of orbit of Mercury.

In Cameron's model, it was proposed that the temperature of the gaseous disk separated was high, probably higher than 2000 K, but in the future, after compression stopped, its intense cooling occurred mainly as a result of radiation. At this initial stage of condensation, particles of the solid substance were formed and the nebula was converted to gas and dust. With an increase in luminosity and the flux of corpuscular radiation of a young Sun, the material from which the large and small planets had accumulated was partially /55
swept out. The particularly large loss of matter of the Sun and the protoplanetary nebula often is related to the period of cooling of the young stars themselves at the stage of T Taurus when their activity

sharply increases and almost half of the initial mass of the star is lost (intensity of solar wind is increased by a few millions of times). Then, due to the proton radiation of the protoplanetary nebula, light short-lived isotopes can form such as Al^{26} and Be^{10} whose role we will talk about later. Although usually we assume that this stage began at the moment of completion of the basic phase of formation of planets, nevertheless, the fact itself of the sweeping out requires assuming that the initial mass of the nebula significantly exceeded today's mass of bodies which are part of the solar system.

However, with the mass on the order of the solar, difficulties arise with transmission of angular moment for a comparatively short time. Therefore, as an alternative, Cameron looked at a model which separated a nebula with a mass ≈0.1 of the solar on which hundreds of thousands of years later, after separation from the Sun, matter continued to accumulate which had passed from its exterior fields. A distinguishing characteristic of the Shatsman model is the assumption that all of the parts of the separated protoplanetary nebula first had identical angular velocity and later on, moving on almost radially from the Sun increased their moment of the quantity of motion. Within the framework of this mechanism, attempts have been made to explain the slowdown in rotation of hot stars formed in the chaotic fields of interstellar clouds of the Orion nebula type and, the possibility of transmitting the moment of the pulse to the planet.

Another approach was made by the well-known Swedish physicist H. O. Alven which considers that a protoplanetary disk (in the Laplace polynomials and its sequences) did not exist and that the planets were formed from plasma clusters ("cloudlets") remaining after separation of the Sun from the primary interstellar gas-dust cloud. During their incidence on the Sun which possesses a strong magnetic field, due to the effect of the electromagnetic forces, a transfer occurred of angular moment at the same time that the role of turbulence was, in Alven's opinion, insignificant. Determined in this process (and in the process of formation of interstellar clouds), he considers the effect of electrical fields occurring analogously among the initial protoplanetary matter in the environs of a young Sun and the /56 magnetospheres of the planets (Earth, Jupiter). In this model, diagramatically shown in Figure 9, by means of a mechanism which can be compared to the effect of an auroral current system, the particles of the "cloudlets" strongly rarefied (without collision) plasma, had to in a comparatively short time (≈one million years) acquire an angular moment lost by the central rotating body. (Alven does not exclude then the possibility of a noticeable contribution to the loss of angular moment of the Sun by the solar wind.) In a much longer process of accumulation of matter (≈100 million years) from these gas-dust "cloudlets" planetesimal began to form which already possessed at that time an unnecessary angular moment and from them by collision with gravitational interactions were formed planets and satellites, in /57 the final analysis.

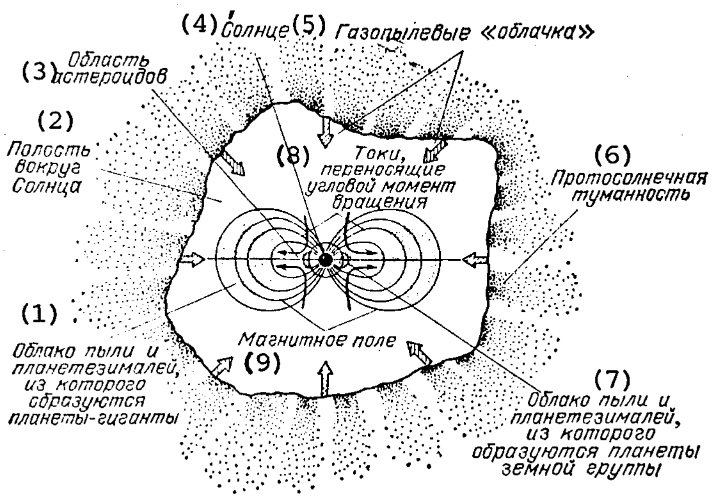

Figure 9. A model of the formation of the solar system according to H. Alven. The remainder of the protosolar nebula in the form of gas-dust "cloudlets" of plasma are incident on the separated Sun possessing a strong magnetic field. Due to the electrical currents arising, transfer occurs to them of the angular moment of the Sun for a short time. Later on, in a more long-term process of condensation of these clouds, solid particles and planetesimals are formed which retain the moment of rotation acquired. The fat arrows indicate the postulated mechanism of transfer of part of the matter from the Sun to the protoplanetary disk formed according to the model proposed by T. V. Ruzmaykina (see text on page 200 [of the original text].
Key: 1. cloud of dust and planetesimals from which the planet-giants formed; 2. space around the Sun; 3. field of asteroids; 4. Sun; 5. gas-dust "cloudlets"; 6. protosolar nebula; 7. cloud of dust and planetesimals from which planets of the Earth group are formed; 8. currents carrying an angular moment of rotation; 9. magnetic field.

The idea that the formation of a protoplanetary nebula occurred under the effect of an explosion of a supernova star in the environs of a compact gaseous cloud (as a result of fragmentation of a more massive gas cluster) from which the solar system arose has gained great popularity. In this case, one can successfully most definitely explain the anomalies of isotopic composition of the nearest media of meteorite matter of analogs of the solar system found as carbonaceous chondrites which can occur due to the injection of materials during the explosion. The presence of Al^{26} generated most probably in this process indicates, in particular, the presence of its daughter isotope -- magnesium Mg^{26} and enrichment of the matter of these meteorites with inclusions of aluminum and calcium in which it is uniformly distributed. This idea is also favored by the data of astronomical observations. They prove a necessity for excess exterior pressure in order to cause a gravitation collapse of a diffuse cloud similar to the parent cloud of the solar system and separation of the disk. This excess pressure can be guaranteed due to shock waves generated by an explosion of a supernova star.

ORIGINAL PAGE IS
OF POOR QUALITY

The problem of accumulation of planets after the protoplanetary nebula has already formed was developed in our country under the direct influence of Shmidt's ideas and a large development was obtained in the works of his students and followers. L. E. Gurevich and A. I. Lebedinskiy, V. S. Safronov, and B. Yu. Levin studied the dynamics of gravitational bodies after the development of perturbations in a thin gas-dust disk and its decay as a result of the occurrence of gravitational instability and also the sequence of accretion of matter on the bodies with intermediate dimensions -- the nuclei of clusters and gradual depletion by them of smaller bodies in the process of the evolutionary cluster. An important role in the process of such accumulation could have been played by turbulent vortices due to which the particles were accelerated and easily combined in the "rings" of matter (according to Safronov's theory).

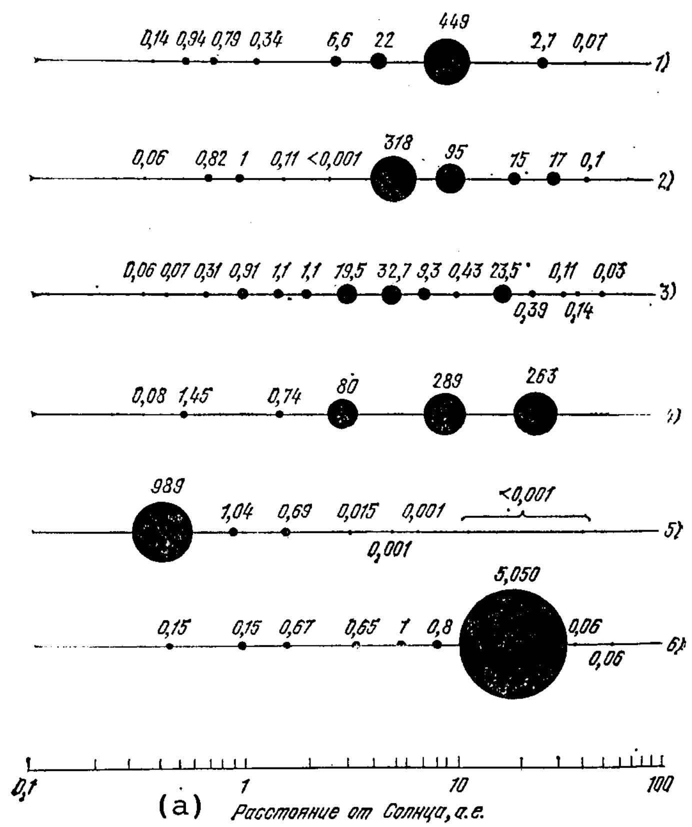

Figure 10. Calculated models of the morphology of a planetary system (according to C. Sagan and R. Isakmen). Variation 2 corresponds to the solar system. Key: a. distance from the sun, IAU.

Less than 15 years ago, experiments were begun on numerical modeling on a computer of the process of accumulation of planets. Experiments by the American scientists S. Doyle, C. Sagan and R. Isakmen led to the conclusion of the basic possibilities of formation of the nucleus of uniform solid-body particles -- planetesimals and the occurrence of commensurability in the positioning and parameters of the orbits and also a multiplicity of more morphology of planetary systems, depending on the number of initial hypotheses. /58
This latter result reproduced in Figure 10 has particularly great interest, giving us concepts of the significant positioning in masses of the planets of the solar system as one of the possible realizations (second diagram in Figure 10) among the other approximately equally probable. At the same time, it is evidence of the large morphological variation in planets of the system which one can expect to encounter in the universe.

A significantly new approach to the theory of formation of planetary and satellite systems is being developed currently by Soviet researchers T. M. Eneyev and N. N. Kozlov. The authors have considered the evolution of a flat protoplanetary cloud in the process of close approach of pairs of bodies moving in Keplerian orbit in the field of attraction of the Sun. The basically corrected concept of this mathematical model is the effect detected as a result of numerical calculations of the annular compression of matter of the cloud and formation (coagulation) of the primary "loose" gas-dust clusters filling to a significant degree their sphere of attraction and slowly compressing due to internal gravitational forces. Then it seemed that the effect itself of annular compression does not depend on the dimensions in mass of initial bodies of the cloud or, as they say, is invariant in relation to it. Here the necessity for the usually used assumptions about the important eccentricities of particles of a protoplanetary cloud in a system of exhaustion loses its importance. However, the stability of such loose bodies requires additional foundation. /59

In the framework of this approach, a certain common criterion was put forward for the formation of planetary systems which made it possible to better understand the concept of the Titius-Bode empirical law. At the same time, a deep connection was detected between the process of formation of the orbit and the mass of the planet and the character of their intrinsic rotational movement. In particular, a precise correlation is found between the low mass of Mercury and the very low rotational moment of Venus which decreases the foundation for the hypothesis of Flendern and Harrington mentioned earlier about Mercury as a satellite of Venus. It was found, moreover, that there is a fairly simple explanation of the existence of forward and reverse motion of planets through a system of forward and frontal blows by asteroid-like bodies in the final stage of accretion.

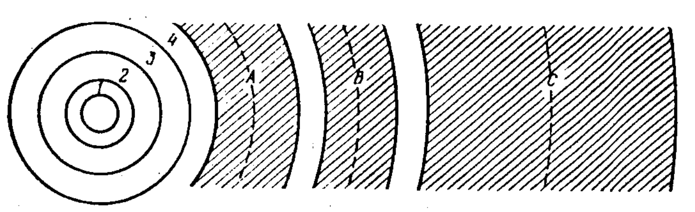

Figure 11. Position of the internal asteroid bands (according to T. M. Eneyev's model); 1-4 -- the orbits of Jupiter -- Neptune, dashed lines A, B, and C -- average of the lines of the bands.

In Eneyev's and Kozlov's theory, the tidal evolution of rotating movement of planets at an early stage must have occurred much more rapidly than today. In the process of further compression to modern dimensions, the change in periods of rotation and inclinations of axes basically led to values existing in all planets, including Venus and Uranus. For Venus, the situation in these initial assumptions was similarly considered by V. V. Beletskiy and his colleagues. The authors came to the conclusion that the "proto-Venus" possessed from the moment of formation of reverse rotation could be captured in resonance rotation for the first 10^7-10^8 years of its existence. /60

Under the effect of tidal forces, subsequent evolution occurred in the direction of slow "upsetting" from reverse rotation to forward; however, for this interval of time, deviation of the axis of rotation from the reverse appeared within limits of 2° and later on decreased even more. In this way, Venus was successfully captured in a resonance rotation but did not successfully change direction of rotation. This mechanism is attractive because the capture of Venus in resonance is impossible to explain due to tidal phenomena in the existing conditions in distinction from situations with the Moon and Mercury.

The model of the annular compression leads also to a fairly basic hypothesis about formation during evolution of a protoplanetary gas-dust disk in certain accumulation zones of the near-Neptune region of several asteroid bands diagrammatically shown in Figure 11. As a result of gravitational interaction inside the bands, particularly the asteroids of band A, part of which are incident in the sphere of effect of Neptune, a rapid and strong transformation could have occurred in their orbits and migration in the field lying inside the orbit of Neptune with subsequent drop in perihelions of these bodies close to the Sun right up to regions of the planets of the Earth group. Such a mechanism which probably acted more effectively during the first billion years of existence of the solar system makes it possible to fairly simply explain the peculiarities of the orbit of Pluto along with its satellites, the orbit of the asteroids in the Apollo and Trojan groups and also striking of large meteorites on the surface of planets of the Earth group in the later stages of their formation.

CHAPTER III

SURFACES OF PLANETS AND SATELLITES

. . . Heavens filled with alder trees
These stars should be laughing
The universe is a deaf place
B. Pasternak
"Sestra moya --zhizn'" 1917

She has sewn herself a dress of stone
Paul Elyuar
"Estestvennyy khod veshchey" 1938

The face of the planet is its surface. The structure forms of /61
the surface, the peculiarities of the terrain, the physical and chemical properties of individual characteristic regions (provinces as the geneologists say) contain the most important information about the present and past of the planet, principles and chronology of events which formed its modern appearance. Very often the processes occurring in the remote geological epochs are apparent in one or another characteristic of the terrain even when the primary structures themselves appear to be strongly camouflaged by subsequent processes or to have been subjected to breakdown and drift (denudation). Much depends here on the relative role and specific features of the appearance of internal (endogenic) and external (exogenic) factors in the formation of the surface structures and the sequence of stratification of these sedimentary layers. Therefore, besides the relief, the greatest importance for decoding and reading the "rock manuscript" essentially are the surfaces of the planets where one can study and compare the rock components, their element and mineral composition. Definite information about these properties is carried by the characteristics of reflection of solar light of the planetary surface which are compiled with the spectra reflection of Earth minerals. This method, first used in the 1960's for the Moon, later on were widespread when studying Mercury and particularly the asteroids which made it possible to classify them according to characteristics. At this time, ten classes of asteroids have been isolated with approximately identical reflective and color properties within the limits of each class. A number of scientists consider, truly, that with a calculation of the differences observed in the spectra of reflection, not gathered into these classes, one can /62
isolate 80 different groups.

In distinction from the planets of the Earth group and satellites of the planet-giants, the planet-giants themselves are massive gas-liquid bodies and do not have solid surfaces. During observations from Earth onto the disk of Jupiter, a system of bands is clearly pronounced with a broad range of colors which have historically given the zones and bands their names. A detailed stratified structure, although considerably less pronounced, is apparent on the disk of Saturn. At the same time, on Uranus and Neptune (appearing green due to the strong absorption of red and yellow beams with methane) no details are observed in photographic surveys of these planets received from high-altitude balloons even with resolution up to a quarter of an angular second which comprises approximately a sixteenth part of the angular diameter of Uranus and an eighth part of Neptune. In 1983, however, using the high-sensitivity instruments already mentioned, the PZS-detectors, an image of Neptune was successfully obtained on which one could precisely trace separate clouds both in the northern and in the southern hemispheres; a study was begun of the time of their life. On the Uranus disk, as before, no irregularities were discovered.

The sequence of processes of formation of the surfaces of the planet of the Earth group rises to the completed phase of accretion when the flux of asteroid bodies incident on the surface were close to disappearing. In this period, usually there were large partially modified craters on the lunar continents similar to the morphology of craters on Mercury and the more ancient strongly eroded craters on Mars. Traces of this stage, probably, are retained on Venus; on Earth, the result of the existence of the hydrosphere and the biosphere not only of ancient times themselves but also of the more recent structures, there appear intense erosions or burial under powerful sedimentary cover. Moreover, the photographs of the surface of Earth from space have made it possible to distinguish a number of ring-shaped structures, which are, obviously, traces of impact bombardment.

Unfortunately, of all of the planets, only Earth is still available for study by all different types of tools which are available now for geology, geophysics and geochemistry. Moreover, only about 15-20 years ago, we did not know approximately 2/3 of the surface of our own planet was covered by water layers of oceans and seas. Hydroacoustic methods have made it possible to "see" the bottom of the oceans. Numerous ships equipped with special devices -- echo sounding which measures depth in the time of propagation of a reflection from the bottom of the sound signal; the underwater relief was studied in detail, showing a number of phenomenal structures which do not have analogs on the Earth's continents. Variation of these structures is shown in a physiographic map (Figure 12). Primarily, this includes a system of mid-ocean ridges, a band of deep-water troughs and island arches, numerous separate underwater mountains and volcanoes. /63

The system of mid-ocean ridges which have intensely rugged relief has a global character. This system is a clearly expressed mobile band extending along the bed of all oceans for a length of about 64,000 km and partially extending onto the continent. The most typical middle ridges that the Indian and Atlantic Oceans, whose individual elevations rise above the ocean bottom by 3.5-4 km. Along the center of the middle-ocean ridges extend large tectonically active broken structures -- rift zones which are narrow slots with steep walls width up to a few dozen kilometers, length from dozens to hundreds of kilometers and depth 1-4 km. They were framed by mountain

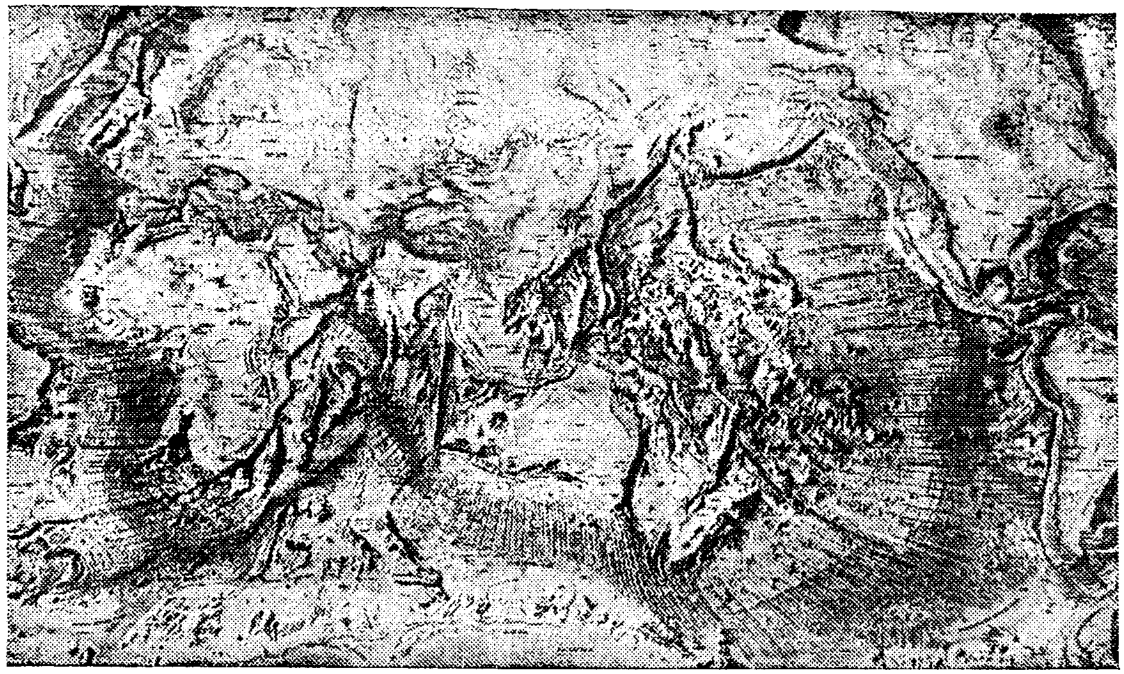

Figure 12. The relief of the surface of continents and the ocean floor of Earth (according to B. Khizen and M. Tarp).

strata (horsts), separated by inter-mountain depression-grabens with relative gradients of the relief 2-3 km. For rift zones of middle ridges, a high degree of seismicity is characteristic and modern volcanism is apparent. To no small degree, these processes are inherent in island arcs and the deep water troughs adjacent to them. These are areas of modern mountain-forming processes on Earth. Here most often earthquakes occur, volcanoes erupt, and this facilitates slides and accumulation of matter due to which often the bottom of the troughs are smoothed out. The systems of volcanic island arcs border on the west of the Pacific, the northeast of the Indian, the west and south of the Atlantic Oceans. The large area of the ocean bottom also has extensive hilly and flat plains, separate individual free-block elevations and volcanic ridges. The tops of some of these volcanoes /65 protrude over the water surface forming islands.

According to the modern view, having received the title of new global tectonics or tectonics of the lithosphere plates, the middle-ocean ridges are considered as zones of rising convective flows in the mantle of Earth and the entire lithosphere is broken into separate large blocks of the Earth's crust -- the lithosphere plates. There are six such basic plates: Eurasian, African, Indian (along with Australia), Pacific Ocean, American and Antarctic. The ocean lithosphere plates which have a thickness from 10-20 to 70-80 km lying on the asthenosphere (intermediate between the crust and mantle layer with reduced strength; more details about this willbe given in the chapter on the inner structure of Earth and the planets) develop on both sides of the axis of the middle ocean ridges under the effect of the horizontal component of convective current originating deep in the interior as a result of dense differentiation of Earth matter in the oxide-iron nucleus and the silicate shell-mantle. The rift zones are formed in areas of movement of the plates where fractures occur along which the hot mantle matter rises upward. With its cooling and crystallization, a new crust of the oceanic type is formed on the edges of the plate; that is, constantly a process of renewal of the crust is occurring. In turn, the ocean plates move up (deepen) along the edge of the continents or the continental, lithosphere plates on the boundaries called Zavaritskiy-Ben'of zones going at a slope under the continent at a depth of a few hundred kilometers. In these zones, (subduction zones) an increase occurs in the new continental crust as a result of upward movement under these plates of the ocean crust and its subsequent floating; island arches occur in areas where the plates slip.

The shift of lithosphere plates along the Earth's surface occurs at rates not exceeding 15-18 centimeters per year. However, for the time characteristic for processes of geological evolution (hundreds of millions of years) such shifts can already reach thousands of kilometers. One can explain the drift of the continents on Earth in just this way.

For studying the relief and physical-chemical properties of the surface matter of the Earth's continents and the bottom of the oceans, there are practically unlimited possibilities and they can be widely /66
used everywhere. In truth, the studies are limited to sedimentary, igneous and strongly changing (that is to say, metamorphic) rock of the Earth's crust. The thickness of the sedimentary cover increases the farther one gets from the axes of the middle-ocean ridges and in these same directions, rock deposited which has undergone the least changes, the "basalt layer" of the crust increases. The results of drilling super deep wells into the oceans from the specially equipped Glomar Challenger ship led to the same conclusion; this was a very effective method inasmuch as the ocean crust is significantly thinner than the continental crust.

The situation is different on those heavenly bodies in which the surface matter did not undergo such significant changes as it did on Earth, inasmuch as there were no effective sources for accumulation of sedimentary rock caused by the presence of a hydrosphere and atmosphere. Primarily this applies to the Moon and Mercury. With the positioning of the Earth and the Moon comparatively close to each other, the astronomers quite naturally "took it" that the morphology of the lunar surface, the relief and many other properties visible from the Earth's hemisphere had been adequately studied in detail. The Moon had become the first object on which the new tool of planetary research had been most ably used -- the studies from the spacecraft. For ten years, tremendous effort was made to obtain photographs of the backside of the Moon before landing the first lunar expedition. Now, many regions of the surface are being studied in detail (Figure 13) on which the traces of the feet of the cosmonauts and the wheels of the lunokhods remain; many years of study are being carried out of different geological structures, the seismic nature of the lunar cores, the thermal flux from the interior, the intensity of erosion of the surface, etc.

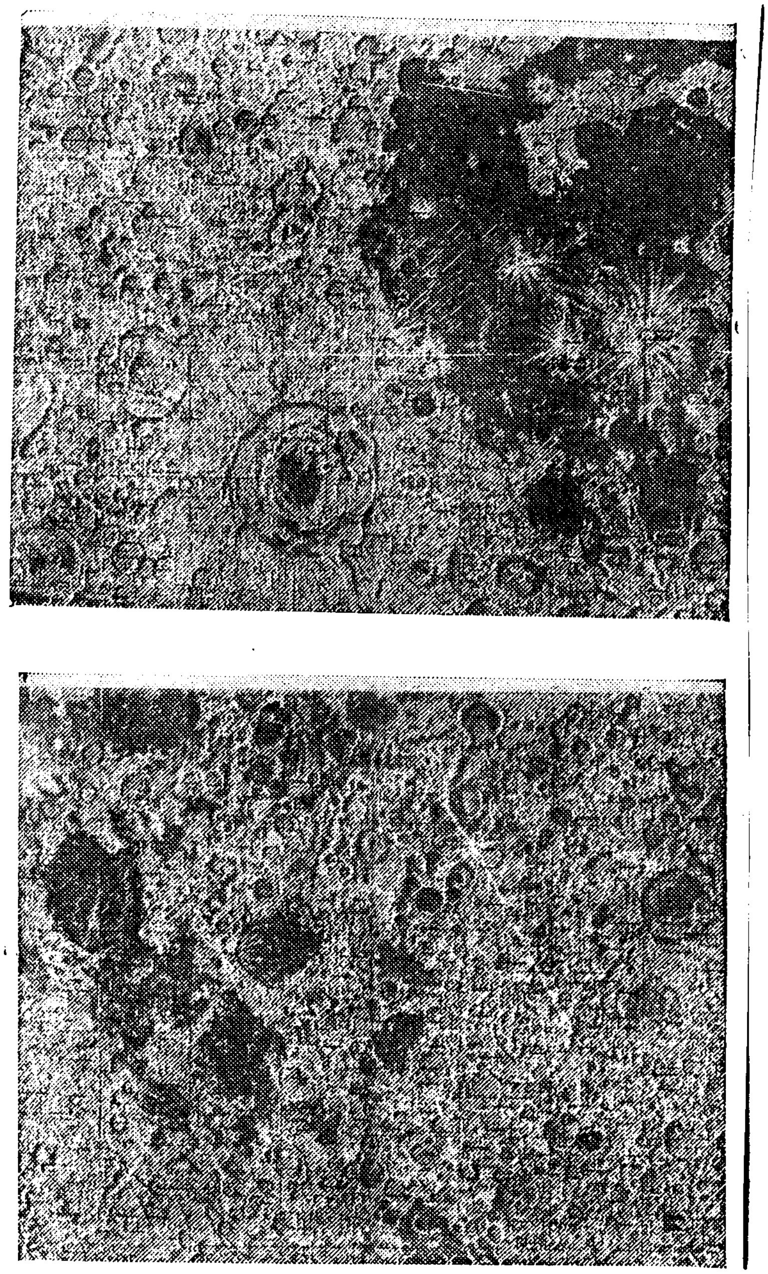

Figure 13. Relief of the surface of the Moon.

But, of course, the most important, from the point of view in dating and decoding geological processes, of the processes occurring on Earth in the precambrian period (more than 570 million years ago) are the results of analysis of lunar soil sampled by the lunar automated probes and the expeditions of the Apollo spacecraft, samples taken from several "sea" and "continental" regions of our natural satellite. Moreover, the knowledge accumulated is still inadequate to be able to "read" the ancient history of the Moon without error (and /68 analogously, of the Earth); soon we will talk about the fact that the results obtained are very hopeful and we must continue intensive work in this direction.

Optical and Radiophysical Methods. Properties of the Surfaces

During observation from Earth by telescope on the surface of the Moon, details extending for somewhat more than 1 km are differentiated. Such a resolution is adequate to study in detail the morphology of comparatively large-scale formations. However, on the basis of these observations, it is impossible to say, for example, what the surface is like according to its mechanical properties. Here, among astronomers there is no unified opinion which adequately recalls the fact that hypotheses were put forward about a thick layer of dust in which the spacecraft can actually "drown" when it lands on the lunar surface. As we now know very well, these dangers were not correct (this was first shown in 1966 by the Soviet Luna-9 automated probe) although the upper layer of the Moon itself actually appeared to be fairly loose consisting of fine, comparatively weak bonded particles. This is called regolith.

As to the planets and their satellites, the studies of the relief of their surfaces lie beyond the limits of the capabilities of optical astronomy. Of all of the planets, only Mars is more or less suitable for ground observations. The best available resolution (about 500 km) makes it possible to separate on its surface only the individual light and dark regions with changing outlines, historically obtained, similarly to the largest details of the relief on the Moon called the "continents" and the "seas," and the white polar caps close to the poles.

Due to the extremely dense atmosphere and extensive clouds, the surface of Venus in an optical range in general is not visible but angular resolution with observations of Mercury is approximately 300 times worse than with observations of the Moon. Therefore, even with the best telescopes, on a disk brightly illuminated by the Sun, one can differentiate only a few of the large dark details. The visible contrast of them is less in comparison with the continents and seas on the Moon. Moreover, in features shown by the solar beams on Mercury, and particularly in their polarization and also thermal emission of this planet in the infrared range of the spectrum, there is much more /69 in common with the Moon. This has led us to the hypothesis that, like the surface of the Moon, the surface of Mercury is covered with a layer of crushed rock similar to lunar regolith. The temperature of diurnal and nocturnal hemispheres of the planet was also measured. It is natural that a close distance from the Sun and in the absence of the atmosphere, the contrast of temperatures is considerably greater than on the Moon. In the region of the equator, the temperature of the surface drops at night to minus 165°C (108 K) and in the daytime when the planet is found in the perihelion, the surface is heated up to +480°C (753 K).

It is well known that in its structure and chemical composition, the lunar seas and continents are close to the continent and ocean depressions on Earth. While in the composition of the seas primarily there are rock-forming minerals of the pyroxene type (enriched with iron and magnesium), the continents were formed by lighter feldspar rock (in which aluminum and alkaline metals predominate). It appeared that up to a certain degree this analogy can be extended to Mercury inasmuch as it reflects the electromagnetic radiation almost the same as the Moon. This is confirmed by the characteristics of its intrinsic thermal radiation, by similar values of parameters of thermal inertia. Mercury, however, has somewhat less reflective capability (albedo) than does the Moon in the visible field of the spectrum. For explaining this feature, a hypothesis was put forward earlier about the increased content in the minerals of the surface layer of iron and titanium which actually can be in agreement with the presence of pyroxene. But later it was found that the spectrum of reflection of Mercury is brighter in the blue and not in the red fields as on the Moon which led to the opposite conclusion about depletion of the surface layer in theses metals. Estimates show a content in it of iron oxide within limits of a total of 3-6% which confirms the concept of differentiation of matter which has occurred in the interior of the planet.

Differences in reflective capabilities of the surface of "seas" and "continents" on Mars were caused by the properties of the material primarily fairly loose and crushed but with different predominating fractions of particles. A comparison of data about spectral dependence of the albedo of the Martian surface with laboratory spectra of reflection of the Earth soils in the visible and the near infrared ranges of wavelengths showed that the dark regions here most of all, is crushed basalt with grain dimensions more than 0.5 mm /70
and in the light regions, the grain dimensions are less than 0.05 mm. Actually, in its mineral composition, the soil in areas of landing for the Viking craft, on the whole, it appeared to correspond to igneous basalt-like rock, however, with relatively large content of iron and less silicon. This is evidence of the fact that differentiation of matter of the Martian interior was less complete than that which occurred on Earth but moreover, is an independent additional confirmation of the geological activity of the planet in the process of its evolution. The average value of density of the upper layer of soil determined by measurement from satellites using infrared radiometers (1.5-2 g/cm^3) was confirmed by the results of analysis of the degree of deepening of supports of descent craft and operations with soil-sampling devices (1.2-1.8 g/cm^3). The values obtained are considerably larger than density of soil on the Moon but noticeably less than on Venus.

Clay which is rich in iron and hydrated metal oxides in the surface layer of Mars possibly show the definite effect on water exchange between surface and atmosphere and impart to it a characteristic reddish shade of rust similar to the coloration of the Earth's desert. It is not by chance that one of the largest deserts in Turkmeniya is called Kyzyl-Kum which means Red Sand. Thus, many scientists who have studied its reflective and color characteristics propose that the rust color of Mars is caused by water oxides of iron. At the same time, the measurements of the element composition on the Vikings have led us to conclude that the soil is 80%, probably, clay minerals (montmorillonite and nontronite) and oxides of iron comprised of about 5% (the remainder -- magnesium sulfate and carbonates). This soil can be formed as a result of erosion by ultrabasic and magmatic basic mountain rock (dunite, basalt) in conditions of a dry atmosphere of a planet practically devoid of oxygen.

The inhabitants of Earth on Mars would be completely unused to the fact that they would encounter circumstances where the temperature of its surface undergoes much greater seasonal-daily variations /71 reaching almost 100 K. However, the amplitude of daily variations rapidly decreases with depth -- approximately by two for each 5 cm so that at a depth of a few dozen centimeters, the variation in temperature is practically absent. This makes it possible to talk about an extremely low thermal conductivity of Martian soil (making a definite contribution to the so-called parameter of thermal inertia obtained directly from measurement of radiation of the surface in the infrared and radio ranges) which are important results for planetary meteorology. We will return to this problem somewhat later.

As we have already mentioned, at the beginning of the 1960's, for studying periods and directions of rotation of planets and as a result of the relief and physical properties of their surface, radar began to be successfully used. For a short period of time, its capability grew considerably as a result of improvement both of the equipment and of the measurement methods. For determining the periods of rotation, results of analysis of the value of shift and expansion of spectral lines of reflected radiation (echo signal) caused by the Doppler effect were used and for studying profiles and properties of the surface, data on the intensity of reflected radiation and the distribution of intensity according to spectrum were used taking into consideration the lag time for arrival of signals to the receiving antenna and the Doppler shift in frequency. Important information on the microstructure of the surface is given to us also by measurement data of the degree of polarization of the radio waves reflected by the planet.

Unfortunately, radar research is more informative for the low-latitude fields inasmuch as, when transferring to high latitudes, this means removal from the region closest to Earth (sub-radar) which makes the greatest contribution to reflection, error in measurement and ambiguity in their interpretation increases sharply. The working range of frequencies for ground radar stations determined taking into consideration minimum absorption in the Earth's atmosphere, encompasses a broad band of wavelengths from millimeters to meters. Centimeter waves are primarily used in radar astronomy.

Radar study of the surface of Mars was particularly intense at the end of the 1960's and the beginning of the 1970's until this method was practically replaced by the powerful flow of information /72 from artificial satellites of the planet. The best resolution available in this period amounted to 8 km in length and about 80 km in width within the limits of a latitude band of $\pm 20^{\circ}$ on both sides of the equator. Significant variations were detected in the Martian relief reaching altitudes of 14 km on a global scale. In certain sections with tens and hundreds of kilometers, numerous gradations in altitude were apparent of 1-2 or more kilometers, most of which, as results of photographing Mars from spacecraft later on proved, were correctly associated with craters with cross sections up to 50-100 km. At the same time, the scattering properties of surfaces and angles of inclination of sections were determined simultaneously; these sections are comparable in extent with their wavelength. The larger the angles are, the greater the roughness of the surface is or, in other words, the more irregular the microrelief. It seems that sections of the Martian surface from which radio waves are reflected, as a whole, are fairly smooth: the root-mean-square values of angles of their inclination $\overline{\theta}$ lies within limits from 0.5 to 4° which is considerably smaller than on the Moon or Mercury.

The intensity of the signal reflected by the planet depends on the coefficient of reflection K (expressed in percentage points) with which physical properties of the surface are directly related (primarily density of the surface layer at a depth on the order of several wavelengths of the probe radiation) and the character of the smooth surfaces of rock. The value of dielectric penetrability ε of the material from which the electromagnetic wave is reflected is determined by these properties. For different dry land, the rock, in an experimental way was found as a simple empirical dependence between dielectric penetrability and density. In this way, measuring ε, it is possible to determine the density of soil ρ on the planet. This method was successfully used for the first time when studying the Moon. The radar study of Mars showed variation in dielectric penetrability of its surface in broad limits, approximately from 1.5 to 5 which corresponds to a value of density from 1 to 2.5 g/cm^3. These estimates were confirmed later by measurement using onboard radiometers in the centimeter range operating on Mars satellites, the /73
Mars-3 and the Mars-5. The broad range of values obtained evidence of the change in properties of the Martian surface from hard rock to very crushed loose rock which as we will see later on actually occurs in different regions of this planet.

The power of signals reflected form Mercury is approximately one to one-and-a-half times less than that from Mars and Venus. Therefore, for radar research, Mercury is a particularly difficult planet. Studies of the function of scattering and polarization of radio emission in the centimeter range of wavelength led us to conclude that on its surface there are many small irregularities. The average values of the angle of inclination in several sections of the equatorial region is estimated to equal approximately 8° -- twice as large as that on Mars. Irregularities of the relief were detected reached in sections with hundreds of kilometers going 1-3 km in altitude. According to the value of the coefficient of reflection of Mercury in the radio range, which appeared to be almost the same as that on the Moon, an average value of dielectric penetrability was found, $\varepsilon = 3$ which corresponds to density of the surface layer of about 1.4 $g \cdot cm^{-3}$. This value is intermediate between the dense surface rocks of the Moon and Earth and, as we see, the much lower average density of Mercury; this is an important result when solving the problem of its inner structure. A summary of the results of radar studies of the Moon, Mercury, Mars and Venus, according to the data of V. A. Kotelnikov is presented in Table 3.

TABLE 3
THE CHARACTERISTICS OF THE SURFACE OF THE MOON AND PLANETS OF THE EARTH GROUP ACCORDING TO RADAR DATA

Planet	k, %	ε	ρ, g/cm^3	$\bar{\theta}$,degree
Moon	5,7-6,3	2.6-2,8	1.2-1.3	6-7
Mercury	5,8-8.3	2,7-3.3	1.2-1,6	5-8
Venus	11-18	4-6	2-3	2,5-5
Mars	3-14	1.4-4.8	1-2,5	Ø,5-4

For Venus, surrounded by a dense, gaseous cloud, radiometers are the most effective means for studying this planet and the width of the "window of transparency" for the surface studied or probing its /74 radiation is minimum. Radio waves in a range approximately from 3 to 3Ø cm is, essentially, a single electromagnetic radiation almost without hindrance passing through the Venusian atmosphere.

According to the results of measurement of the intensity of emission in centimeter waves at the end of the 195Ø's, for the first time, a hypothesis was put forward that the surface of Venus can be anomalously hot. First of all, it was assumed truly that another interpretation of these results based on the model of a cold surface but a super dense ionosphere is that its radiation is explained by the high radio brightness temperature of the planet. The arguments in favor of a model with a hot surface were more convincing, however. Actually, as was shown a few years later, the direct measurements on the Soviet Venera automated probe, the surface of the planet is heated up to a temperature of 74Ø K. The question of how large the temperature differences were between night and day in the hemisphere was argued for a long time; values up to several tens of degrees Kelvin were discussed, and the argument was particularly about equatorial and polar regions. Radio astronomy measurements showed that there is a basis for considering that the poles are one hundred or more degrees colder, but this has not been confirmed. Right now we can consider it proven that the daily variation of the surface is practically absent and the difference in temperature between the equator and the poles hardly exceeds a few degrees Kelvin. This is explained by the fact, as we will see somewhat later, that the thick atmosphere of Venus which has tremendous reserves of heat has larger thermal inertia and intense circulation exchange. Therefore, even in the long Venusian night (58.4 Earth days), the surface found under such a dense hot "fur hat" is not successful in cooling off noticeably in any way and due to the constant acting mechanism of transfer of atmospheric gas in a meridional direction, a variation occurs of temperatures between the equator and the poles. The basic reason for the actually existing temperature differences on the surface is the gradations in altitude related with the relief.

In the centimeter range of radio waves, it is possible not only to study the surface but also to "see" it as it looks. For this, a high spatial selectivity of the reception antenna on Earth is necessary. Usually, this is achieved by receiving a reflected signal on two antennas located at a certain distance from each other /75 operating according to the principle of a radio interferometer. According to the difference of the phase of the signal received, the position of each section of the surface relative to a certain average level shape of the planet is measured in sequence. It is obvious that the higher the spatial selectivity of the antenna, the higher is the resolution on the surface of the celestial body being studied and, correspondingly, the higher the quality of the image. With this method, called a frequency-time selection method, for example, images were obtained of the Moon which are difficult to distinguish from the ordinary photographs obtained using ground optical telescopes.

According to the data of numerous radar probes in the band of Venus near the equator, variations in relief were not as significant as they are on Mars. Typical gradations of altitude appeared within limits 2-4 km in sections of length up to 400 km. Moreover, according to the data of reflection of radio waves, concepts about the significant irregularity and physical properties of its surfaces have been merged. More complete data on the reflecting capabilities were obtained at the following American stations: Goldstone in California and Aresibo in Puerto Rico. In Goldstone, reception of reflected emission was carried out on two antennas with diameters 64 m and 26 m, spaced at 21.6 km, and in Aresibo, the largest in the world, a 300-meter antenna was used, installed in a crater of an extinct volcano. This made it possible to obtain a picture of the reflection characteristics of the surface in a latitude band ±70° and "images" of several separate sections with cross-sections 1500 km close to the equator.

The picture of the band near the equator obtained according to measurements in Goldstone is shown in Figure 14 and a fragment of the map for high latitudes of the northern hemisphere of Venus, according to measurements in Aresibo is shown in Figure 15. For the zero meridian, here, the direction to Earth is selected in the low conjunction. The ratio of intensities of reflection of the light and dark regions reaches 20:1. The broadest light bands are approximately 30° south and north latitudes (longitude 0° and 280°) with cross-section greater than 1000 km detected even at the very beginning of radar studies of Venus and designated as α, β and δ. One more light region close to the zero meridian at a latitude of 65°N was named Maxwell. We see from Figure 14 that an approximately similar light /76 region is located somewhat higher in latitude in the longitude region 310-340°.

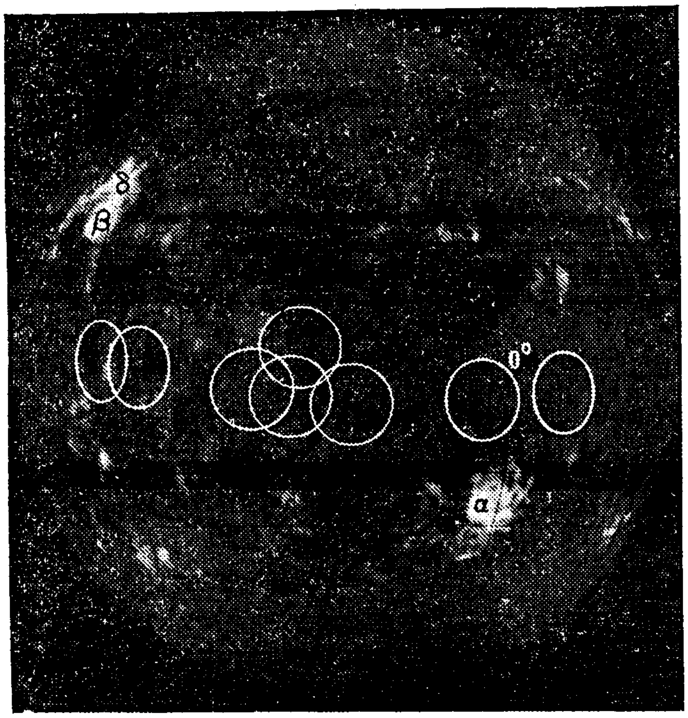

Figure 14. A radio image of Venus in a 12.5 cm microwave link indicating distribution of the reflective properties on its surface in the equatorial and middle latitude surfaces (according to R. Goldstein et al.); the circles indicate regions for which large-scale radio images have been obtained.

How can we explain such large differences in the reflecting properties of the Venusian surface? There are three such basic reasons. The first is the relief: the higher the region, the less the thickness of the atmosphere is over it and this means the smaller the degree of absorption of radio waves. Second is the microstructure of the surface: the rougher it is (in the scale of wavelengths of radar measurements) the larger is the reflection which is minimum in the case of a /78 mirror-smooth surface. In other words, the contribution of a diffuse component to the value of the reflected signal is greater than the mirror or quasimirror components inasmuch as, in the case of a rough surface, the coefficient of directivity of the reflected radiation (defined as the effective area of reflection) is higher. Finally, the third factor is the physical and chemical properties of the surface on which the value of dielectric penetrability of the material ε depends: with an increased ε, the degree of reflection increases. Let us look at all of these possibilities in more detail, relying on the experimental results obtained.

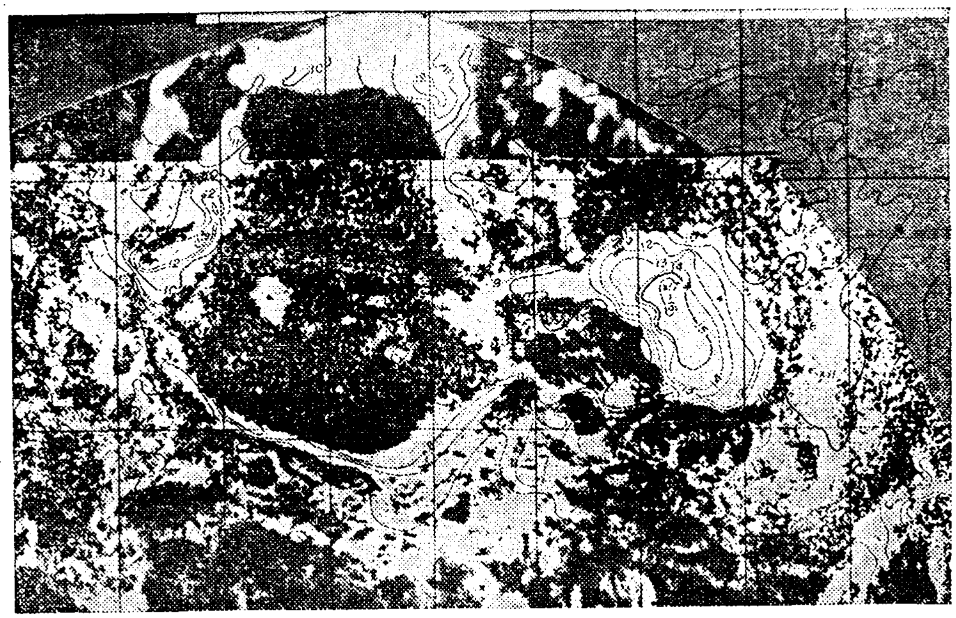

Figure 15. A radio image of a high-latitude region of Venus obtained at the Aresibo Observatory with application on it of isolines of different altitudes according to the data of radio altimetry from the Pioneer Venus satellite (according to G. Pettengill et al.). The isolines indicate values of altitude from a conventional level which is 6.5 km less than the average radius of Venus (6051.5 km).

It is not difficult to understand that even a relatively small variation in relief can make a noticeable contribution to distribution of reflective properties along the surface, simply due to the fact that the densest atmosphere is close to the surface. Actually, gradations in altitude within limits 2-4 km change the thickness of the absorption layer of the atmosphere by approximately 15-25% and with the presence of elevations up to 10 km, the effective thickness is changed by almost two.

The microstructure of the surface strongly affects both the properties of reflection and the degree of polarization of radiation. It was found that polarization of the main part of the energy of radio waves reflected by Venus corresponds to mirror reflection and that the ratio of depolarized reflection to polarized for Venus is considerably smaller than for the Moon. This means that, in comparison with the Moon, the microstructure of its surface on the average is smoother and the large irregularities involve regions with increased reflection of radio waves. The average angles of inclination of surface irregularities estimated are evidence of this; they appear to be included in limits 2.5-5°, that is, approximately the same as on Mars.

Dielectric penetrability of the Venusian surface is changed in comparatively small limits, approximately from 4 to 6; for the average value $\varepsilon = 4.5$, one obtains an estimate of density 2.5 g/cm^3 which is considerably larger than for the Moon and certain regions of Mars and, obviously, is evidence of the absence of porous or fine-crushed rock in the surface layer of Venus. The value $\varepsilon = 4.5$ corresponds to the dry silicate rock of the basalt and granite types whose densities are within limits 2-3 g/cm^3. Actually, the first direct measurements of the character of smooth surface rock on the descent modules of the Venera-8, Venera-9 and Venera-10 automated space probes fully confirmed these concepts. /79

Experiments were carried out using gamma-spectrometers which measured on the surface the natural radioactivity of the rock in the area where the probe landed by recording the intensity of rigid gamma-radiation in several characteristic lines of uranium, thorium and potassium. Radiation is due to radioactive decay of these elements always present in the crust of the planet. The relationship of their intensities is a good indicator of which predominant type of rock makes up the surface layer of the sections studied. This method proposed by academician A. P. Vinogradov was first successfully used on the Moon with the Luna-10 artificial satellite; this made it possible to draw conclusions about the basalt-type character of lunar rock. However, the use of a satellite is possible only when in the celestial body (as in the case of the Moon) there is practically no atmosphere and gamma-radiation without interference reaches the orbit of the satellite. For Venus, landing on the surface gives us a singular possibility for making these measurements. The measurements made in 1972 and in 1975 led us to the conclusion that the type of rock in the landing area of the Venera-8 is close to Earth's granite and in the landing areas of the Venera-9 and Venera-10, basalt predominates. On the Venera-10, the density of the soil was measured at the same time using a radioactive densimeter. From the experiment, a value of 2.7 ± 0.1 g/cm^3 was obtained, agreeing very well, as we see, with the estimate from the radar measurements of ε.

The most complete information today about which rock makes up the surface of Venus was given to us by measurements of the element composition of soil by a roentgeneroadiometric method on the descent modules of the Venera-13 and Venera-14 automated probes. In order to establish the complexity of technical realization of these experiments, one should remember what kind of conditions exist on the surface of Venus and give attention to the fact that the analysis itself of soil must be done with normal temperature and pressure not exceeding 0.1 atm. Therefore, a special soil sampling device was designed including a miniature drilling assembly and a lock chamber for delivering the sample taken inside the module. The system of automatics guaranteed sequential completion of operations of hermetic /80
seal from the environment, a vacuum and a thermostat. A sample of matter delivered to the receiving trough was irradiated by radioactive sources which were isotopes of plutonium and iron and were excited by a spectra of X-ray fluorescent radiation recorded by a block of detectors.

During work on the surface, each station took and transmitted to Earth dozens of spectra, an example of which is shown in Figure 16. They made it possible to determine the content in the sample of the basic rock-like elements from magnesium to iron and in this way to identify the samples being studied with well-known Earth rocks whose spectra have been studied well.

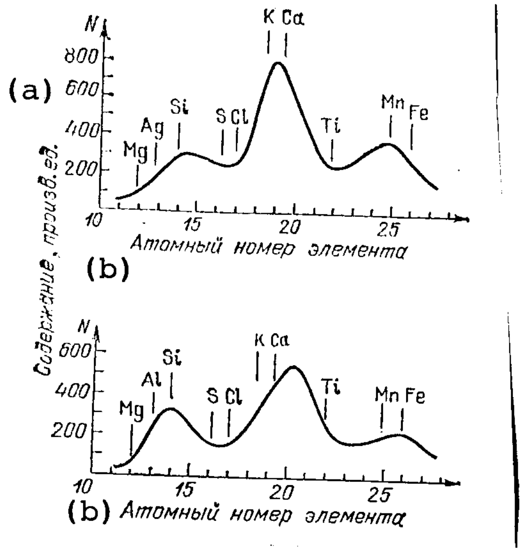

Figure 16. Examples of spectra of roentgenofluorescent radiation of samples of soil obtained on the Venera-13 and Venera-14 automated probes. The content of elements is determined according to intensity of radiation; their position is indicated by the lines along the horizontal axis (according to the data of V. L. Barsukov, Yu. A. Surkov and their coworkers.
Key: a. content, production unit; b. atomic number of the element.

It seemed that in the landing region for the Venera-13, the rock was enriched with potassium and, obviously, did not differ greatly from the rock in the landing area of the Venera-8 where, according to the data of measurements of natural radioactivity, the soil earlier had been found to be approximately the same anomaly in its content of potassium. Moreover, according to its remaining composition, this rock is not close to granite but to the potassium alkali basalt of the Earth's crust which is not widespread, encountered primarily on ocean islands and in the /81
continental rifts of the Mediterranean. In distinction from them, the character of rock in the region of the Venera-14 landing is very similar to the rock identified on the Venera-9 and Venera-1Ø probes. In composition, they remind one of the widespread rock from the ocean crust of Earth -- the so-called toleite basalt characteristic also for ancient lava flows on the Moon. According to the results of recent similar measurements made under the direction of V. L. Barsukov in the near-equator regions of Venus on the Vega-1 and Vega-2 probes, on the surface also a third type of basalt rock was identified, obviously, close in its properties to olivine gabbronorite.

In this way, basalt rock comprising a significant part of the Earth's crust, obviously, is characteristic for Venus. This leads to a hypothesis about the closeness of interaction of the continental crust and the broad flows of basalt on all of the related Earth bodies -the Moon, Mercury, Mars and Venus. It is possible, however, to think that the surface of Venus not only in structural-morphological relationships but also in its chemical composition is more uniform than Earth. This involves the fact that in conditions of a deficit of water (see below), the basalt melts which form the crust of the planet, obviously, did not undergo any kind of significant metamorphic changes and therefore, in comparison with Earth where the situation was different, the type of surface rock on Venus had much less variation.

Relief of the Surface of Venus

In the preceding section, we considered which causes affect the increased reflection of separate regions. But in order to understand what has actually caused the fairly large variation in the reflective properties shown on the map in Figures 14 and 15, additional experimental data are needed. Among these, radio images and high-altitude profiles (altimeter treatment) of the surface are important.

In the 1970's, the first "images" of the surface of Venus from Earth were obtained; the appropriate areas are indicated in Figure 14 by the circles. Within the limits of these areas, resolution on the /82
surface reached 15 km and in altitude 200 meters. An example of the images obtained is presented in Figure 17. They have made it possible to discover a number of large-scale forms in the relief, among which, primarily, there are many craters with diameters from 30 to 150 km. The craters are unusually small and the depth of the largest does not exceed 0.3-0.5 km which is approximately ten times smaller than that for craters with similar dimensions on the Moon or Mercury and at least five times smaller than for the craters of Mars. This undoubtedly proves the smoothness of the Venusian topography in the equatorial regions of the planet.

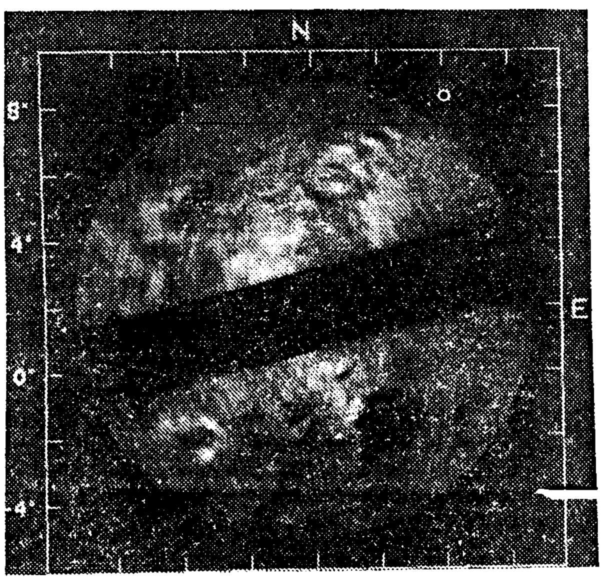

Figure 17. Large-scale radio image of the surface of Venus on which craters are visible. The cross section is about 1500 km. The top is north and the right is east. The black band is an area in which the details of the surface which did not show up with the radio interferometer method.

Even more detailed structures were detected using the radio telescopes mounted on artificial Venus satellites. The prospects in this direction are exceptionally good and even in years in the very near future, one can expect to obtain radio images of the entire surface of Venus which are as good in quality as the photographs of Mars, Mercury, Jupiter and its satellites transmitted from the spacecraft. The importance of /83
obtaining phototelevision and radio images covering the basically new stage in the study of morphology and the physical properties of surfaces, geological history and evolution of planets, is hard to over-estimate. The possibilities of research have expanded

immeasurably not only thanks to high resolution, hundreds of times exceeding the best resolution obtained when photographing from Earth but also thanks to the global encompassing of the entire planet, the accessibility of areas and polar regions which are unfavorable for one reason or another for ground observations. For example, for Venus, during optical observations or during radar research from Earth, it is more convenient, as we have already noted, that the periods of close low conjunction when Venus is turned toward us on one or the other side. Therefore, its other hemisphere and polar regions are hardly studied at all. The use of satellites has easily solved this problem.

The first experiments on radio mapping were carried out in 1975 from the Venera-9 and Venera-10 artificial satellites for which the so-called method of bistatic radar was used. The idea of this method involves the fact that the surface of the planet is irradiated by radio waves from the orbit of the satellite and the radio signals reflected are received on Earth. Further, as during radar from Earth, according to the difference of time of arrival of signals and the width of their spectra, gradients of altitude and the degree of roughness of the surface can be evaluated with the frequency-time method of selection which is already familiar to us (that is, from an analysis of the dependence of intensity of the reflected signal on frequency and time) in order to construct a radio image of the region studied. Several sections were detected with irregular relief in the southern hemisphere of Venus extending in a broad direction for several hundreds of km. The altitude gradients in these sections reached about 3 km and their surface appeared to be slightly rough, almost smooth.

A more effective method of radio mapping was used on the American Pioneer-Venus satellite. Radar is done in this case by the satellite itself without the participation of ground radio telescopes. The satellite emits radio waves and receives the reflected signals back and then the results of radar are transmitted to Earth. The radio waves from the satellite are emitted along the verticals and at a /84
certain angle in relation to the section of the surface being studied. Probing along the verticals makes it possible according to the time of lag and intensity of reflected signals to measure the altitude of the relief and the physical properties of the surface along the flight path of the satellite (as they say, to conduct altimetry). In turn, the inclined probing ("lateral view") makes it possible to obtain a radio image. It is accomplished by the inherent rotation of the satellite with the antenna mounted on it in such a way that the radio beam "slides" along the surface on both sides of the plane of the orbit of the satellite passing through the vertical. The measurements of time delay and the Doppler shift of frequency of reflected signals provide the necessary spatial selectivity even with a comparatively small antenna; however, the quality of the images and the resolution appear very low (approximately 30-50 km) significantly inferior to images with resolution of a few kilometers obtained in recent years by D. Campbell at the Aresibo Observatory. Nevertheless, the results of the radio altimetry, in combination both with the ground and with the satellite radio images, significantly clarify the nature of the

reflecting properties and features of the relief of many regions of the surface of the planet.

A new important step on the path of studying relief and physical properties of the surface of Venus was the launch in 1983 of the Soviet Venera-15 and Venera-16 artificial satellites. For studying radar images of the surface according to the principle of lateral view, on them a much improved piece of equipment was installed developed under the direction of well-known Soviet scientist, A. F. Bogomolov. The subsequent inspection of sections of the surface along the orbit in a band about 150 km wide, length up to 8000 km, was accomplished at a certain angle relative to the local vertical (within limits 10°) and then not due to rotation of the satellite itself with the antenna as in the experiment on the Pioneer-Venus satellite, but by electron scanning with a radio beam in a direction perpendicular to the plane of the orbit. For this purpose, a special antenna with elliptical shape was used with maximum dimension 6 m. The brightness of the photographic tone on the images was determined by these same three factors on which intensity of the reflected signals depend during radar from Earth. Resolution on the terrain reached 1-2 km. /85
At the same time, when using a radio altimeter-profilograph with high precision, relative gradations in altitude were measured and using the radiometer -- the temperature of the surface. As a result of inherent rotation of the planet for each subsequent rotation of the satellite new regions were studied and processing of data on the computer at the Institute of Radio Engineering and Electronics of the Academy of Sciences, USSR made it possible to "sew" together separate bands connecting the transmitted images with relief of the terrain and the thermal physical properties of the surface of Venus.

Located in near-polar orbits with pericenters close to the north pole, the Venera-15 and Venera-16 satellites, for almost a year of work made surveys of the northern hemisphere including the polar and middle latitudes (up to ≈30°) of an area 100 million km^2 which corresponds to approximately a quarter of the entire surface of the planet. This made it possible to study these regions with the greatest amount of detail, significantly improving our understanding of the special features of morphology of the relief and its connection with geological processes, and to begin a compilation of high-quality maps. How do we look at the planet closest to Earth on the basis of the information that we have today?

Figure 18 shows a map of the relief of the surface of Venus with average resolution about 100 km. The light sections are the plains and the dark are the elevations. It is apparent that almost 90% of the surface of Venus lies within the limits of ±1 km from the average level corresponding to a radius 6051.5 km at the same time that the greatest elevations occupy an area of less than 8% of the surface. In this way, as a whole, Venus appeared to be the most spherical of all the planets with a smooth relief. But still there are some very steep mountain massifs. On a fragment of surface indicated in Figure 15,

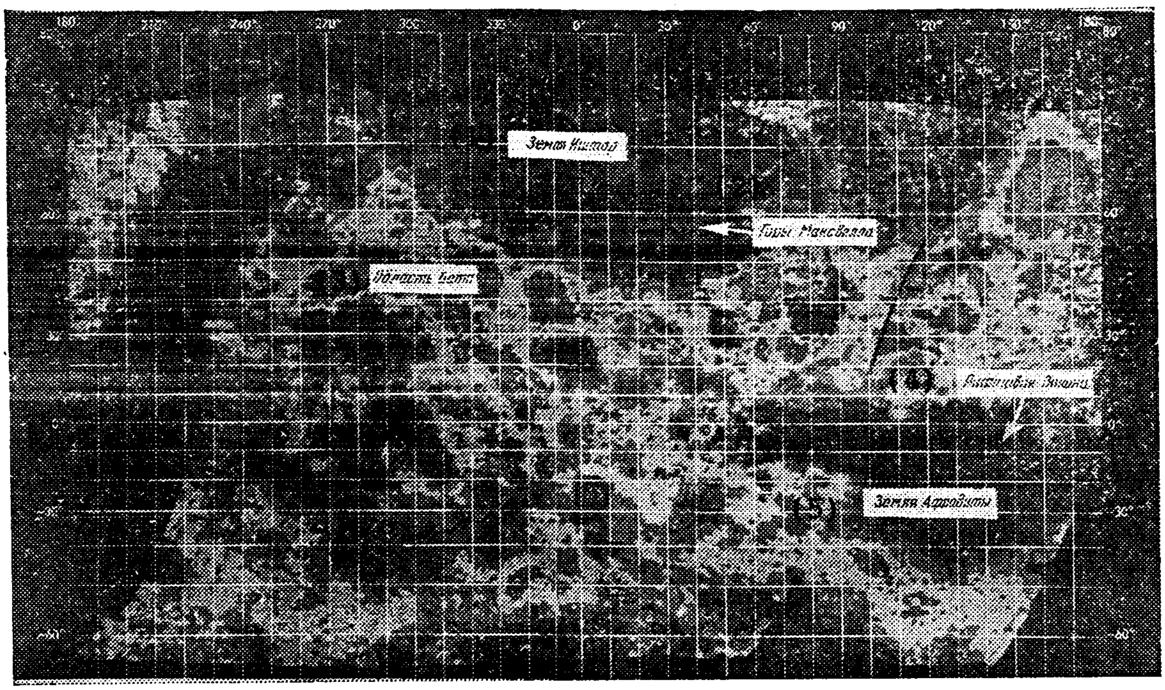

Figure 18. Map of the surface of Venus constructed according to the results of radio altimetry from the Pioneer-Venus orbital craft. The light areas are plains, the dark elevations among which the largest are called Terra Ishtar and Terra Aphrodite. Also, the Maxwell Mountains and the Rift Valley are shown.
Key: 1. Terra Ishtar; 2. Maxwell Mountain; 3. Beta Region;
4. [illegible]; 5. Terra Aphrodite.

horizontals are applied -- lines with uniform altitude for a certain conventional level of the surface adopted during radar measurements (which is 6 km lower than the average). As we see, practically the entire region is a tremendous elevation. The light area -- the Maxwell Mountains which was already mentioned were ioslated especially (Figures 18, 19) and also two mountain massifs (Freyn and Akny Mountains) to the west and to the north from them on a broad, dark, flat mountain with pear shape extending for more than 5000 km. The altitude of this entire mountain region called Terra Ishtar (named after the female goddess in Assyrian-Babylonian mythology) is at least 4-5 km and the ridges ringing it are several kilometers higher. /87
From adjacent plains, it is separated by steep precipices. One of the peaks at the center of the Maxwell Massif reaches an altitude of 12 km over the average level of the surface almost one-and-one-half times /88
exceeding the highest peak on Earth, Mount Everest. On the slope of this mountain, there is a tremendous volcanic crater with diameter 95 km whose bottom is almost two kilometers down. It is interesting that inside this crater one can detect one more crater with diameter 55 km lying almost a kilometer deeper than the base crater. The entire region undoubtedly has a tectonic origin and simultaneously an

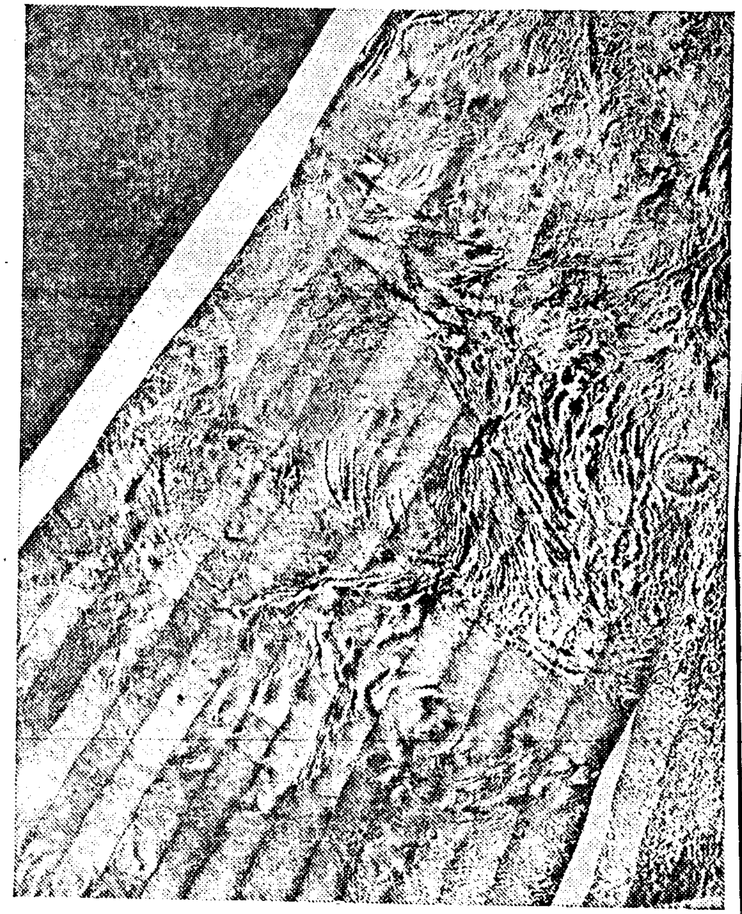

Figure 19. The Maxwell Mountains (on the right) and the eastern part of the Lakshmi Plateau. The darkest region in the Maxwell Mountains is the highest massif, whose highest peak reaches almost 12 km. On the right edge of the photograph, a tremendous volcanic crater is visible on the slope of the mountain; its cross section is 95 km. It is a montage of radio images transmitted from the Venera-15 and processed at the Institute of Radio Engineering and Electronics (at the Academy of Sciences, USSR).

important role was played by volcanic activity in the formation of the structures observed.

Similar expressions can be given about the Alpha region, also formed by a broad, flat mountain named Terra Aphrodite -- named for the goddess of love and beauty in ancient Greek mythology identical with Venus. Within the limits of this flat mountain, two broad elevations are identified. They are somewhat lower than Mount Maxwell and their maximum altitude over the surrounding terrain is 6-8 km. Unfortunately, the resolution achieved is still inadequate to answer the question of whether or not they have large shield volcanoes and whether or not there are specific volcanic craters on their elevations -- caldera, similar to the huge caldera in the Maxwell Mountains.

Besides these phenomenal formations, on the broad areas which have approximately uniform reflecting capability, comparatively small ridges, hills, depressions and troughs are detected among which particularly we have isolated the extensive deep valley in the southern hemisphere. In its dimensions, it reminds one of a rift ravine inside the basic elevation and it is one more proof of the existence in the past of tectonic activity on Venus.

Extremely small, smooth craters of impact origin are evidence in favor of these concepts. We have mentioned craters with cross section up to 150-200 km and depth in all of several hundreds of meters in the radio images of several regions close to the equator (see Figure 17). However, the largest formations detected on the surface of Venus have a depth which is not great also (a total of 500-700 m). It is hardly probable that intense erosion processes (including chemical erosion) played a decisive role in this leveling, although, in conditions of a dense, hot atmosphere containing aggressive admixtures, they could have had an effect. More probably, tectonic activity had the most important effect here. Characteristic traces of tectonic volcanic activity in the form of extensive rock structures including an unusual ring-shaped form of cooled basalt outflows and lava flows are clearly visible on the images transmitted from the Venera-15 and Venera-16 /89 satellites. Judging from the difference in shapes in the relief, the quest of Venus was more than once subjected to processes of intense deformation and broad lava outflows occurred.

Examples of powerful deformation of the crust as a result of tectonic and volcanic-tectonic activity are shown in Figures 19-22. These examples reflect the different types of breakdown in the primary strata of the crust (the so-called dislocations) as a result of which old, ejecta, overthrusts, underthrusts and other tectonic forms develop. Geologists have divided the dislocations into three types: linear old-rupture forms (Figure 20), systems of extensive ridges and valleys with diagonal or orthogonal undersections reminding one of roof tiles or parquet (Figure 21) and unique ring-shaped structures with diameter from 150 to 600 km formed as concentric strata and trenches which are called ovoids (Figure 22). A broad zone of linear fold shapes in the form of a system of almost parallel ridges and valleys with width from 5-10 km to 30-50 km, corresponding to the earth fold band, form the mountain systems mentioned: Maxwell, Freyn and Akny on the Terra Ishtar. As if in a framework of these systems, here one finds the tremendous Lakshmi Plateau whose dimensions are **approximately the same as** those of Tibet in whose central part one detects two flat-bottomed craters with dimensions about 150 km reminiscent of the caldera of the Mars shield volcanoes. The plateau itself, which has an altitude of about 3 km and obviously is covered with basalt, breaks steeply toward the plain adjoining the Terra Ishtar from the south. Here also there are linear dislocations passing along the Vesta outcropping, possibly, formed as a result of pressure on the material from under the plateau on its boundary and also by shear dislocation. B. L. Barsukov, A. T. Basilevsky, and their co-workers put forward a proposition that the ridges of the framework are

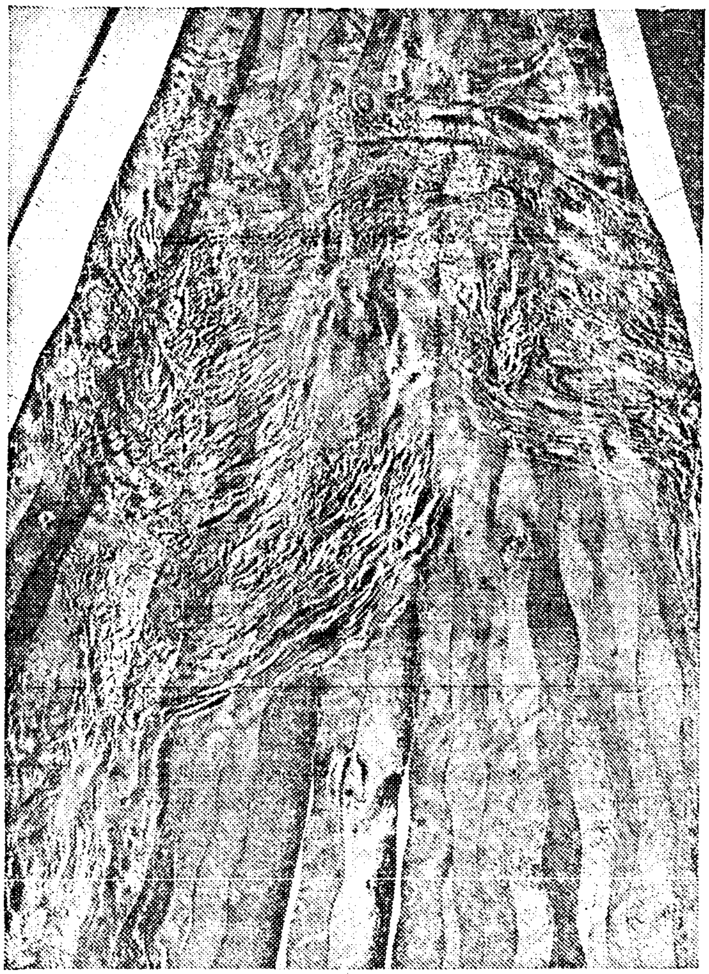

Figure 20. The northern end of the Lakshmi Plateau in the framework of Mount Akny (from the west) and Freyn (from the north). It is the montage of radio images transmitted from Venera-16 and processed at the Institute of Radio Engineering and Electronics (of the Academy of Sciences, USSR) (north is on top).

partially moved up on the plateau or the reverse -- the edge of the plateau is moved down under the ridge. Then this region of Venus can be considered as similar in its character to the transition zone from the ocean to the continent crust or the zones of subduction as they are called within the framework of the hypothesis of tectonics of lithospheric plates on Earth. In turn, on the broad areas with systems of overlapping ridges and valleys ("roof tiles"),sometimes /90
intersected by cracks or stresses of the crust as a result of inner stress (see Figure 21), it is possible to find characteristic traces of classic deformations and trace a certain analogy with systems of fractures and zones of ocean rifts. /91
However, in distinction from Earth, on Venus these characteristics are much more weakly pronounced, in particular, structures are not visible which remind one of troughs with whose existence global processes of plate tectonics exist. Inasmuch as, according to the modern view, the occurrence of these processes on Earth date back to a period of about 1.5 billion years ago, it is possible to think that in the present relief on the surface of /92
Venus there are forms imprinted which are similar to those which, obviously, were in existence in the Proterozoic epic on our planet.

B. L. Barsukov and others call the shapes of the relief retained since ancient times ovoids (see Figure 22). They were most probably formed in the final stage of intense meteorite bombardment soon after completion of accumulation of planets although the obvious traces of /93

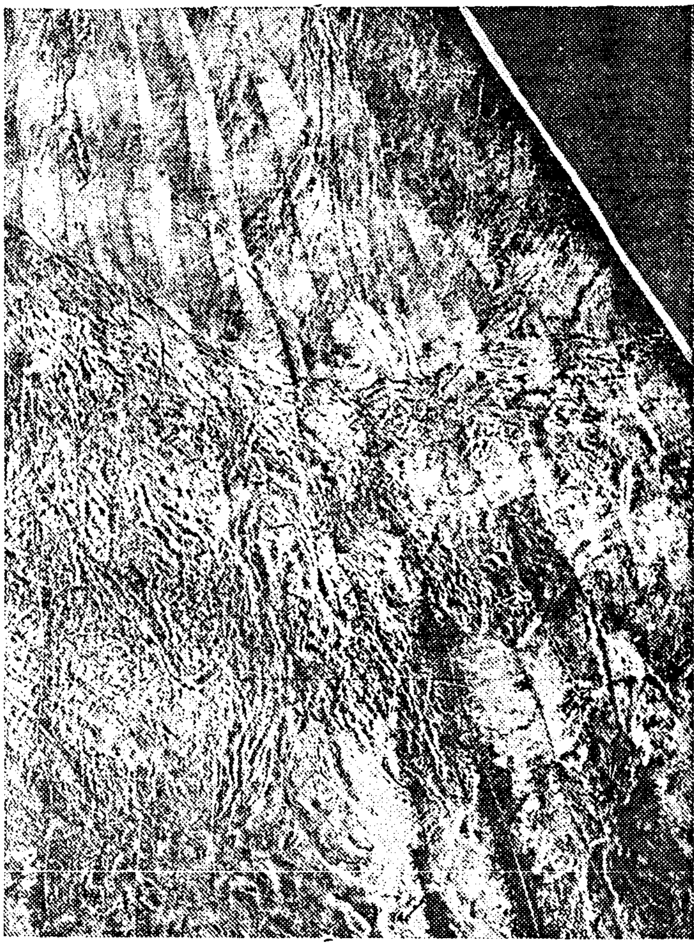

Figure 21. An example of the morphology of the relief which has been named "parquet" or "roof tile." On the photograph is the region to the north of Terra Ishtar. This is a montage of radio images transmitted from the Venera-16 and processed at the Institute of Radio Engineering and Electronics (of the Academy of Sciences, USSR).

impact effect were not retained. Their structure differs strongly from similar precambrian ring-shaped structures on the ancient platforms of Earth occurring during rise to the surface and flow of magma in the area of impact depressions.

Extensive smooth and hilly plains (see Figure 20), besides the ancient caldera, are also evidence of the broad development of volcanism on Venus; probably they were formed by outflows of liquid basalt flux. A more outstanding feature morphologically than the complex hilly plains is the tremendous number of cones and cupolas in many of which craters are visible at the peak. Their discovery confirms the hypothesis that the mechanism of ejection of heat from the core by "scattered volcanism," that is, through several thousand small volcanoes, can be basic for Venus.

Thus, we see, that the surface of Venus is divided into regions which are quiet, not subjected to deformation and strongly deformed bands in which there is a certain analogy seen for Earth. Moreover, the absence of troughs with the presence of compression systems can be interpreted in another way -- that movement of lithosphere plates occurs without subduction as is proposed by Soviet geologist L. P. Zonenshayn. The latter, probably, involves the fact that in distinction from Earth, the lithosphere on Venus is easily an asthenosphere and due to its buoyancy cannot be deeply immersed.

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Figure 22. Ring-shaped structure of the Nightingale on the southern end of the Tephiya region. Such structures are called ovoids. The montage of radio images was transmitted from the Venera-15 and processed at the Institute of Radio Engineering and Electronics (of the Academy of Sciences, USSR).

Hypotheses about mobility of the Venusian crust related to processes of geological activity and the Venus-wobbling were put forward back in 1975 after receiving the first phototelevision panoramas of the surface transmitted from the Venera-9 and Venera-10 descent modules. They made it possible for the first time to look directly at the landscape of our neighboring planet (Figure 23). It seemed that in the area of landing of the Venera-10 located to the southeast of the Beta region, a well-known elevation reflected by radio waves (see Figure 14), there is a level stone desert without any kind of noticeable gradations in altitude. The large rock block on which the module landed, with cross section not more than three meters, is variegated with dark spots, probably, not to too great a depth, and is filled with soil. /95

The block and others similar to it at some distance from the module, is immersed in the darker soil. The entire landscape, obviously, is an outcropping of the crust magma rock which has undergone significant changes due to the effect of high temperature and pressure of the atmosphere. In the central part of the block, there are clear traces of a crevice and a number of additional cracks on the edges. Their formation can involve both the interior processes occurring on Venus and impact from landing of the module on the surface -- the true cause cannot be established. Differences in the microrelief of the surface (the presence of honeycombs, hillocks, small ridges and cracks on the blocks) and the degree of filling of separate irregularities with eroded material all reflect differences in composition of rock, their non-uniform resistance to factors of destruction which include obviously, chemical interaction with the atmospheric gases as a definite factor.

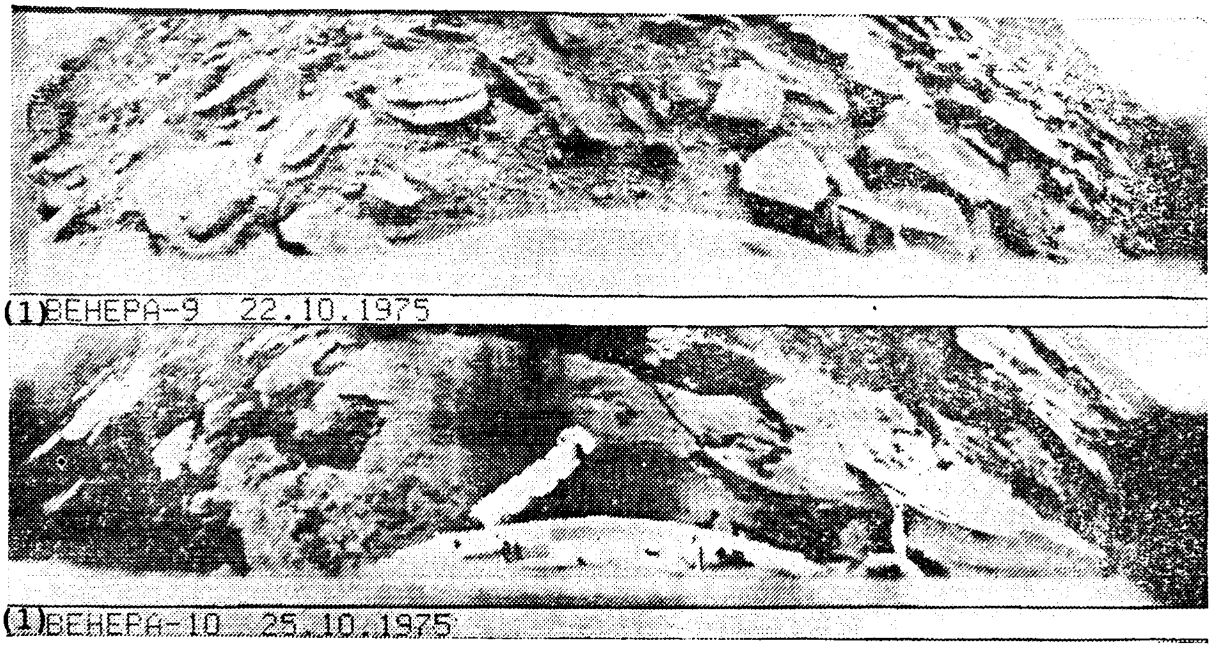

Figure 23. Panoramas of the surface of Venus obtained in the areas where the Venera-9 and Venera-10 probes landed. The regions of the survey are ~ 2000 km one from the other. On the front plain of each panorama, the landing ring of the vehicle and the rod of the densimeter are visible. The dimensions of the large rocks themselves on the Venera-9 panorama are 50-70 cm. Key: (1) Venera

The landing area of the Venera-9 is approximately 2000 km from the place where the Venera-10 landed and is located on the northeast extremity of the Beta region. On the panorama transmitted from this region, primarily attention is attracted by the abundance of large sharp-angled locks which fill approximately half of the area of the surface. The dimensions of the largest rocks reach 50-70 cm, but the altitude is not great -- a total of 15-20 cm. A plate-like shape and graduated broken pieces are characteristic for them. These are particularly visible, for example, in the three flat rocks on the left of the landing ring of the apparatus located, as in the Venera-10 panorama, in the form of a segment in the lower part of the photograph. The space between rocks is filled with comparatively light material, obviously, a fine-grain soil formed in the process of breakdown and deformation of surface rock. This can be compared with the lunar regolith like the primary rock covered with fragmentary material in the landing area of the Venera-10. On individual rocks, dark spots are visible -- possibly traces of erosion similar to those which we talked about when looking at the Venera-10 panorama.

The origin of the landscape on the Venera-9 panorama is most probably caused by a breakdown in primary rock under the effect of internal shifts and fractures in the crust of the planet. As a result, a rocky talus is formed on the slope of the elevation on which the module landed. The steepness of this slope is about 30°, the line of the horizon, in distinction from the Venera-10 panorama, is at a distance of several tens of meters. The rocks, obviously, are fairly strong and have not undergone noticeable breakdown. It is possible to think that this landscape itself is fairly typical for elevations and ravine areas of Venus and was formed comparatively recently (on the geological scale of time). It is also possible that periodic movement of rock on the slope occurs as a result of the assumed seismicity of Venus. /96

Even more high-quality panoramas of the surface, including color images, were obtained in 1981 from the descent modules of the Venera-13 and Venera-14 automated probes. Their landing regions were also selected in the direct environs of the high-Beta plateau, in the Pheba region, where hilly elevations and smooth lowlands predominate. For transmitting television images, as shown in Figure 24, television

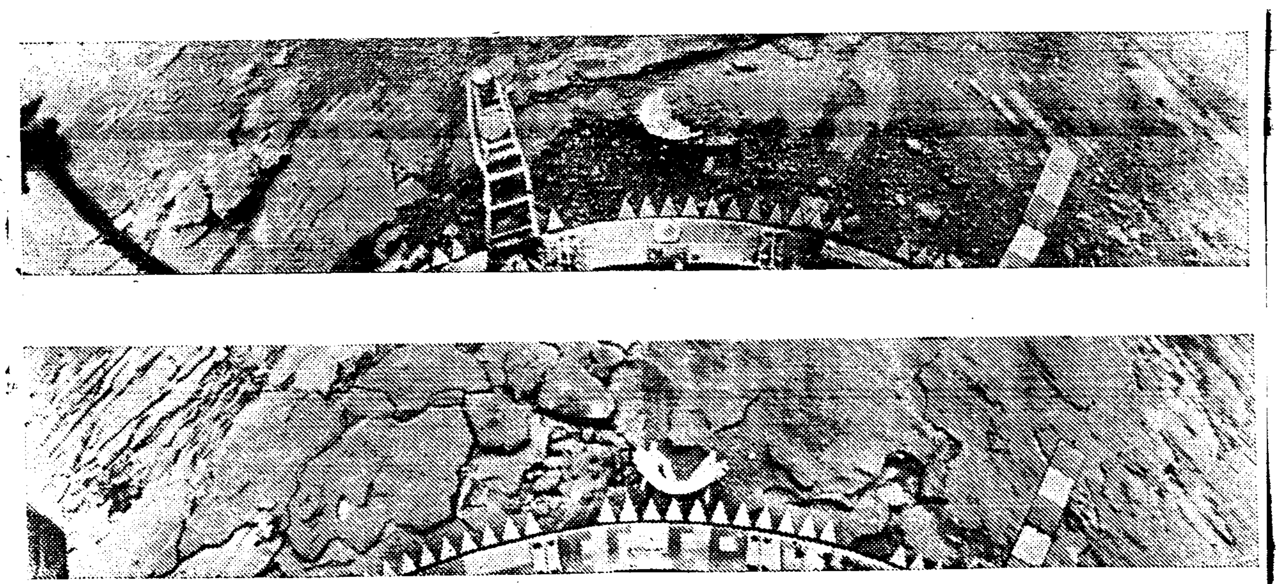

Figure 24. Panoramas of the surface of Venus sent from the Venera-13 probe (above) and the Venera-14 (below). Each of the panoramas encompasses an angle of approximately 180° on both sides of the probe; one of them was obtained through color light filters with subsequent synthesis of colors. Elements of the structure, covers of the portholes, ejected after landing, the color test table are all visible. In the angles of the image, one observes the line of the local horizon and a section of the sky. For characteristic features of the landscape, see the text.

cameras were used which were improved in comparison with those mounted earlier on the Venera-9 and Venera-10. On each page, two television cameras were installed with fields of vision 37°X180°. With the altitude of the porthole over the surface 0.9, it was possible to have an almost 360° view of the landing area. Inasmuch as the axis of the panoramas is slanted at 50° to the vertical, transmission of the landscape and resolution of the details on the terrain are the same: the middle part of the panorama contains an image of the surface directly in front of the camera at the same time that the edge sections are images of more distant areas up to the horizon visible as a slanted line with pieces of sky over it. By combining the images obtained through the blue, green and red light filters, color panoramas were synthesized (for one, full, that is, 180° and one within the limits of the angle of 60° on the opposite sides of each module). In the field of view, the television camera captures the ring support of the module with the toothed frame (it was designed for increasing stability in the parachute-free descent section; the distance between the teeth is 5 cm), the band of the colored test (on the right), the grid structure of the instrument for determining the physical and mechanical properties of the soil (length 60 cm) and the rejected semicylindrical lids of the portholes of the television /98 camera with diameter 20 and height 12 cm. The figures presented give us an idea of the relationship of dimensions on the surface; the precise values and mutual positioning of details are determined according to the results of photogrometric analysis.

Even a cursory examination of the panorama shown in Figure 24 proves that both landing regions have a definite similarity in their morphology and do not differ greatly from the panoramas of the Venera-9 and Venera-10 probes. The clearly pronounced outcroppings of rock in the Venera-13 panoramas rising slightly over the surface remind one of the rock slabs on the Venera-10 panorama. The depressions between them are filled with a layer of loose soil, due to which these sections of the surface appear to be darker. A horizontal lamination of rock is clearly noticeable in the landing region of the Venera-13 similar to that which can be seen on the fractures of individual rocks in the rocky talus on the Venera-10 panorama.

Multi-layer horizontal lamination is even more clearly visible on the Venera-14 panoramas and the areas of light and dark layers alternate; there is almost no loose soil. The thickness of individual layers does not exceed a few centimeters and their number reaches ten and more. Uniformity of the microrelief traced at a distance of dozens of meters from the module is evidence of the cyclic stratification on the surface of the material differing in chemical composition or granulometry as a result of uneven reflective properties of the layers. In individual areas, traces of a breakdown (thinning out) are noticeable sometimes overlapped by later deposits. Geologists have presented a hypothesis that such a surface texture is characteristic for stratification of the sedimentary type; this means that its formation is due to processes of sedimentation accumulation. The sources of such processes could be volcanic eruptions with subsequent precipitation on the surface of the products of ejecta (cinder) in a quiet atmosphere or delamination of the magma flows which, however, is more probable due to small thickness of the individual layers. This does not exclude the idea that products of sedimentation accumulation are well known in the Earth tufa according to whose composition igneous rock of the basalt-like type is appropriate. Although more definite expressions have been put forward about the origin and development of these rocks, it is still difficult obviously to have a single proof that the active geological processes occurred on Venus in the not-too-distant past.

Relief of the Surface of Mercury

Talking about Venus or any other planet of the Earth type, the planetologists usually start with concepts of the complex ways of their evolution, at least in the very early stages, let us say for Earth -- appropriate to the early Archean period (more than three billion years ago). However, traces of these stages are covered by different stratifications of later formations. The only exception here, obviously, is Mercury and in the early stages of the Moon inasmuch as basic hypotheses exist that were confirmed in the process of formation and evolution of the powerful effect of Earth. Along with the asteroids, Mercury can be considered the best example of a relict retained for the stage of formation of large planets. This sort of "plaster cast" of this stage has definite traits for its surface similar to that of the modern atmosphere of Jupiter and the comets; obviously it contains information about the matter of the protoplanetary nebula in the period preceding the beginning of accumulation of the planets.

From the flight trajectory of the Mariner-10 spacecraft, in 1974, more than 40% of the surface of Mercury was photographed with a resolution from 4 km to 100 m (for certain sections) which made it possible to look at Mercury approximately the same way as we look at the Moon from a telescope on Earth. Examples of the phototelevision images obtained are shown in Figures 25 and 26. The abundance of craters is the most obvious trait of this surface; at first glance it seems similar to the Moon. And it is not surprising that even the specialists in selenology who looked at these photographs immediately after their reception assumed that they were photographs of the Moon.

Actually, the morphology of craters is close to the lunar, their impact origin does not cause any doubt: in the majority, a clearly outlined swell is visible, traces of ejecta of material crushed during impact with formation in a series of cases of characteristic bright beams and a field of secondary craters. In many of the craters, a central hill and terrace structure of the internal slope are visible. It is interesting that such features have not only practically all of the large craters with diameter above 40-70 km (which is observed on Earth) but also a significantly larger number of craters with small dimensions within limits 5-70 km (of course, we are talking about well /101
retained craters). These special features can occur both due to large kinetic energy of the bodies deposited on the surface and due to the material of the surface itself.

The degree of erosion and smoothing of craters is different. For example, clearly noticeable radial structures mean that it is not great at the same time that in a number of craters hardly noticeable fragments are retained. On the whole, the Mercury craters, in comparison with the lunar, are less deep which also can be explained by the large kinetic energy of meteorites due to acceleration larger than on the Moon of the force of gravity on Mercury. Therefore, the crater formed during impact is effectively filled with ejected material. For this same reason, the secondary craters are located closer to the central than on the Moon (ballistic trajectories are steeper) and deposits of crushed material, to a lesser degree, mask the primary shapes of the relief. The secondary craters themselves are deeper than the lunar, which again is explained by the fact that the fragments falling on the surface undergo a force of gravity which is more strongly accelerated. /102

Figure 25. Phototelevision image of the surface of Mercury close to the south pole. The pole is located on the limb in the central part of the large crater with cross section 180 km (photograph from Mariner-10).

Just as on the Moon, it is possible, depending on the relief, to separate the predominating uneven "continent" and significantly smoother "sea" regions. The latter most expediently can be considered hollows which, however, are significantly smaller than on the Moon; their dimensions usually do not exceed 400-600 km. Some of the hollows are weakly distinguished on the background of the surrounding terrain. An exception is the broad Caloris Basin already mentioned (Sea of Fires) which extends for about 1300 km and reminds one of the well-known Sea of Rains on the Moon. It is possible that there are other similar basins remaining on the large part of the surface of the planet which have not yet been photographed. The morphology of the framed swells, the fields of secondary craters, the structure of the surface within the Caloris Basin gives us the basis for assuming that during its formation a larger amount of material was ejected than during the formation of the Sea of Rains and that later on there could have sequentially occurred processes of additional settling and rising

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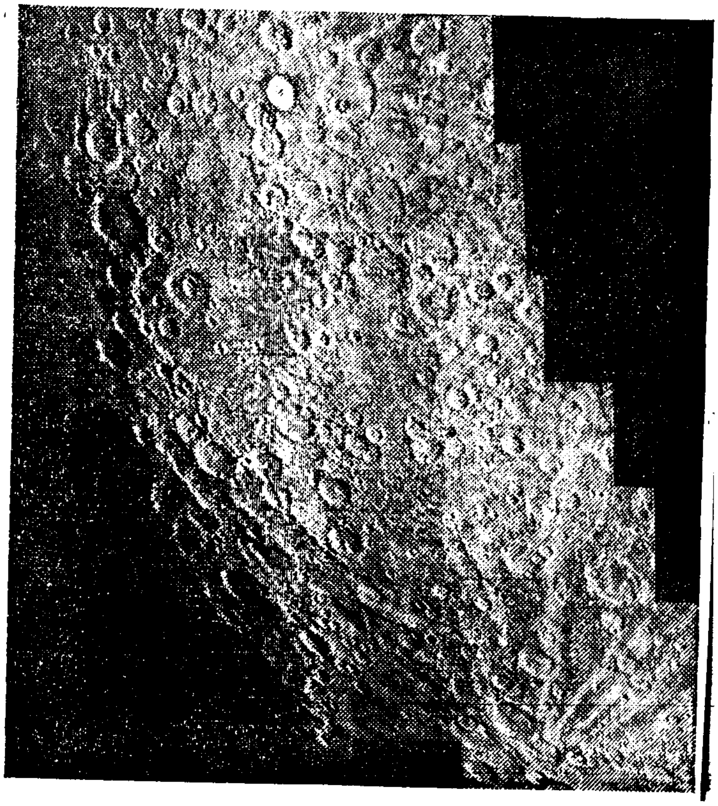

Figure 26. A mosaic of photographs of the surface of Mercury in the middle and upper latitudes at the terminator. Beam structures are clearly visible in the craters in the lower and upper parts of the image (Mariner-10 photographs).

of the bottom related to the possible outflow of magma and isostatic leveling (due to which an equilibrium state for sections of the crust was provided).

In the predominating continental part of the surface of Mercury, it is possible to isolate both strongly craterized regions with a higher degree of degradation of craters and broad territories of old intercrater uplands attesting to the broad development of ancient volcanism. These more ancient shapes of the relief of the planet have been retained. The plain regions of the seas and the sections next to them were formed in a later era. We can judge this from the weak saturation of the plains with relatively fresh craters, the majority /103 of which have small dimensions. The leveled surfaces of the basins, obviously, are covered with a thicker layer of crushed rock -- regolith. Along with a small number of craters, here one encounters rocky ridges reminiscent of the lunar. Some of the sections adjacent to the basin plains, probably, were formed during deposits of material ejected from them. Moreover, for the majority of plains one finds completely definite proof of their volcanic origin; however, this volcanism was of a much later time than the intercrater uplands. The impression is created here that in its morphology and development, these regions of Mercury are very similar to the regions of the lunar seas and the plain surfaces of Mars, whose formation usually is dated for a period at a limit of about 3-4 billion years ago. This same period includes the completion of the stage of the most intense (after the face of accumulation) bombardment of the planet by large bodies as a result of which the "seas" were formed and other large and sometimes less noticeable craters.

Now if we compare the quantity of large basins and craters with diameter more than 200 km on Mercury, the Moon and Mars, then it seems that their density is approximately inversely proportional to the area of the surfaces of these heavenly bodies at the same time that their cross sections differ by a factor of two. It follows from this that the number of meteorites in the regions of space occupied by these planets can be approximately identical. Understanding this is not as simple as one would think at first glance. Usually, we start with the concepts that the basic regular source of meteorites "postulated" in the interior regions of the solar system is an asteroid band and the planets are found at different distances from it. However, if one pays attention to the fact that besides this basic source there can be other similar clusters of asteroid bodies beyond the orbit of Pluto (see Figure 11) also those fulfilling the functions of "suppliers" of meteorites, the difference in the positioning of planets close to the Sun becomes insignificant.

This hypothesis seems more probable to us than the one using similar cases of different "catastrophic" hypotheses. For explaining the principles observed, the well-known American scientist G. Bezerill proposed a hypothesis of catastrophic breakdown of the asteroid under the effect of tidal forces with its passage close to the Earth and /104
Venus and subsequent fallout of fragments. The fragments then could have been distributed within the limits of the field of positioning of the planets of the Earth group approximately uniformly. With all the external attractiveness of this scenario, it is useful, obviously, to mention the well-known philosophy-methodology principle according to which one does not have to invent essentials above the necessary. In other words, one does not have to use exotic explanations if it is possible to get along with simpler ones.

Analyzing the basic traits of the surface of Mercury, we turn our attention both to the many similarities and to the significant differences with the Moon. An attentive study shows one more interesting feature shedding light on the history of formation of planets. We are talking about the characteristic traces of tectonic activity on a global scale in the form of specific steep scarps, or slopes -- escarpments. The escarpments have an extent of approximately 20-500 km and the altitude of the slopes is from a few hundreds of meters up to 1-2 km. According to its morphology and geometry of positioning on the surface, they differ from the ordinary tectonic breaks and ejecta observed on the Moon and Mars and more rapidly were formed due to thrusts laminated as a result of stress in the surface layer occurring during compression of Mercury. The horizontal shift of the swells of certain craters are evidence of this as is seen, for example, in Figure 27. Here, the escarpment which is called East, on a section 130 km long intersects two craters. In the crater with cross section 65 km, located at the center, a shift in the swell is visible at approximately 10 km which obviously was due to the decrease in dimensions of the crater with general retention of the area of the crust of the planet. In the evaluation of the well-known geologist R. Strom, this contraction comprised about 100,000 km^2 which is equivalent to a decrease in the radius of Mercury by approximately 1-2 km. These numbers are small if we relate them to the total surface area or the radius of Mercury; however, the process itself had tremendous consequences for the formation of the relief.

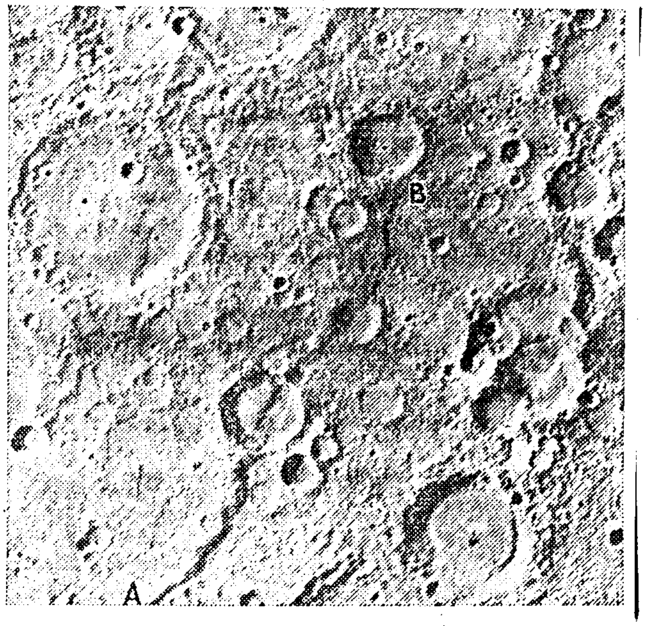

Figure 27. The escarpment (AB) on the surface of Mercury. The escarpment intersects two craters with diameter 55 km and 35 km. The part of the escarpment shown has a total length of exceeding 500 km (photograph from the Mariner-10).

Some of the escarpments were subjected to impact bombardment and were partially destroyed. This means that they /105
were formed earlier than the craters on their surface. According to the degree of erosion of these craters, it is possible to conclude that compression of the crust occurred in the period of formation of "seas" about 4 billion years ago. The most probable cause of compression must, obviously, be considered the beginning of cooling of Mercury, whose thermal history we will turn to again. According to another interesting proposal, put forward by a number of specialists, an alternative mechanism for the powerful tectonic activity of the planet in this period (with the formation of ships, compression and extension, apparent differently in different latitudes) a tidal retardation of rotation of the planet was possible, by approximately 175 times: from the initial proposed value of about 8 hours to 58.6 days! Actually, a number of crests, troughs, linear segments of swells and escarpments have primary orientation in the meridional direction with small deviations toward the west and toward the east which would favor this hypothesis. Moreover, it is impossible to exclude the fact that these characteristics of the surface impressed the inner stresses in the core of the planet under the effect of tidal perturbations on the Sun playing a particularly important role during the formation of such structures in the process of compression /106
of Mercury.

The Surface Relief of Mars

Already very recently, analogues occurring fairly long ago on the Moon have been extended to Mars. They occurred in the second half of the 1960's after which the Mariner-4, Mariner-6 and Mariner-7 flights obtained the first photographs of several comparatively small regions on the surface of the planet in the southern hemisphere. The photographs which would be waited for impatiently were disappointing. The regions photographed had an abundance of craters, the majority of which were strongly broken down and somewhat actually reminiscent of the lunar. Using this very limited information, we begin to talk about Mars as a dead planet, not only biologically but also in the geological sense. This strongly weakened the traditional interest in it by the scientists and society at large which for a long time had been inspired by such exotic phenomena as a "seasonal shift in vegetation cover," "canals," etc. As we look from afar, the attempts to interpret the observed data in these terms actually were incorrect. However, further study, particularly energetically developed after conclusions in orbit around Mars of the first artificial satellites in 1971 (the Soviet Mars-2 and Mars-3 and the American Mariner 9) didn't simply revive but significantly increased the interest in this planet, having discovered essentially a new Mars for us (Figure 28).

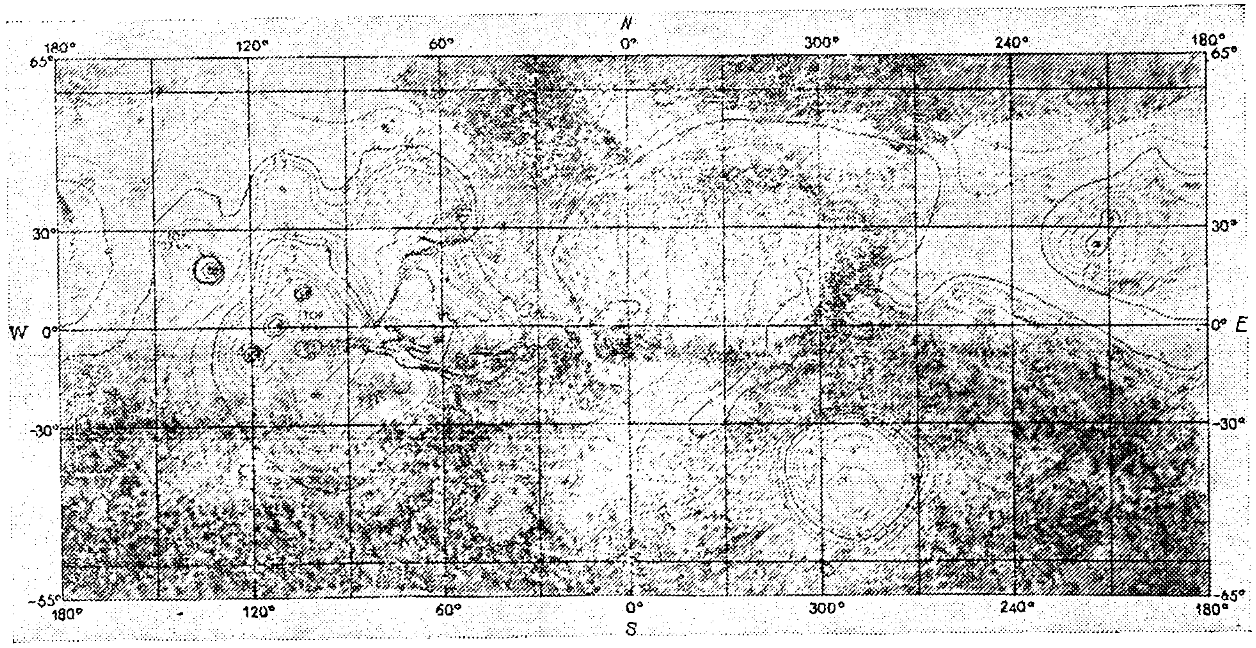

Figure 28. A topographic map of the surface of Mars. The intervals between the isolines of altitude (horizontals) 1 km. The ancient crater surface of the southern hemisphere is adjoined by broad plains of the northern hemisphere with two large volcanic elevations, Farside (0°, 105°W) and Elysium (30°N, 210°W). (The map was compiled by Sh. Vu.)

The results of global mapping of Mars by transmitting television images and photographing the surface from the Mariner-9, Mars-5 and Viking-1, Viking-2 satellites was particularly effective. The images were obtained basically with a resolution of about 1 km, but individual sections were studied with a resolution up to 40-50 m, that is, 10,000 times higher than with observations from Earth! Finally, this made it possible to see that the dark and light areas observed by telescope on the disk of Mars understandably related to periodic changes in their outline and contrasts which are such real boundaries of other weak hardly differentiated spots as polar caps appear to be. /108
Sequential photographs of the same regions for a period exceeding the Martian year, equal to almost two Earth years, made it possible to trace

the dynamics of seasonal variations and the effect of atmospheric processes on the morphology of the Martian surface.

The study of the structure and relief of the surface mainly was facilitated by uniform measurements in other ranges of wavelengths -- infrared, ultraviolet and centimeter. According to the value of effective scattering of radiation in the ultraviolet part of the solar spectrum with a "column" of atmosphere found directly under the satellite, one can determine what the optical density (or so to speak, the optical thickness) of this "column" is under the appropriate sections of the surface and this means the altitude of this section relative to a certain average level. In this way, the altitude profile of the surface was measured along the route of the satellite orbit and because the planet is rotating, this sequential shift of measured sections relative to the plane of the orbit of the satellite (and precession of the orbit itself in space) makes it possible to obtain a global range. Another determination of altitude, independent but using an idea close to the first method, was based on measuring the degree of absorption by molecules of the atmosphere of the reflected solar radiation in one or several characteristic bands in the near infrared field of the spectrum. Such measurements also make it possible to evaluate the optical thickness of the atmospheric column under a given section of surface, depending on the relief of the terrain. These methods supplement the data on the relief very well, data obtained directly from analysis of images taking into consideration the direction of the axis of the lens and the position of the Sun over the local horizon at the moment of photography. Finally, the photometric measurements of the degree of reflection of the surface of solar light depending on wavelength and the degree of its polarization give us information about the characteristics of the soil and the physical nature of the particles.

Indeed, what is the surface of Mars like? First of all, it seemed that the difference already noted in the position of the average levels of the surface of the northern and southern hemispheres due to lack of symmetry in the shapes fairly clearly shows up in the morphology of the relief: in the northern hemisphere, plain regions /109 predominate, and in the southern -- crater regions. Large basins ("seas") with cross section larger than 2000 km are apparent such as the Ellada, Argyr, Amazonia, Crise and elevated plateaus ("continents") -- Farside, Elysium, Tavmasiya, etc. The latter in their dimensions are close to the Earth continent and rise 4-6 km over the level of the average surface, which corresponds to the equatorial radius of the planet 3394 km. While on Mars oceans exist as on the Earth, they are filled with broad spaces of basins and these plateaus actually are isolated like continents.

The physiography of the Martian surface is varied shapes of relief (Figures 29, 30, 31). Besides the broad craterized regions, direction information was detected of tectonic and volcanic activity in the form of characteristic volcanic cones and fractures, combinations of relatively young and ancient structures, fairly precise traces of the effect of different erosion factors and /110 processes of sediment accumulation.

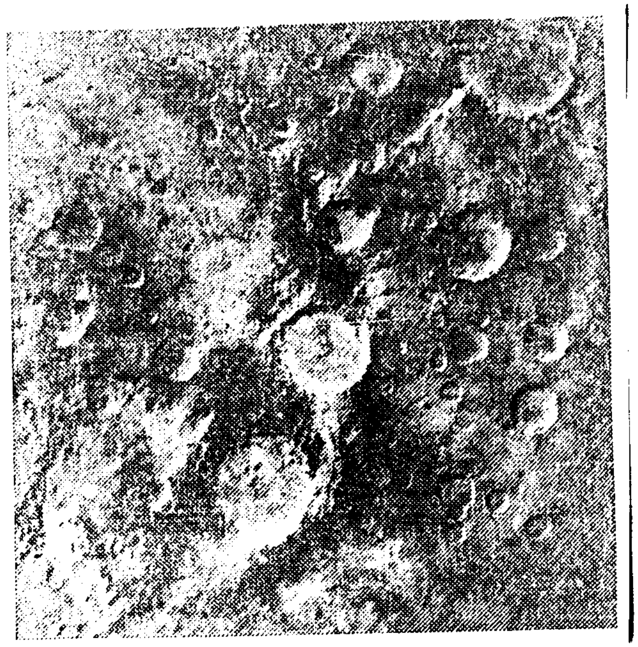

Figure 29. A section of the craterized surface of Mars in the southern hemisphere. In the center of the Bond Crater with cross section 100 km, on the left -- the winding Nirgal Valley. Photograph from the Mars-5.

The overwhelming majority of craters primarily concentrated in the middle and high latitude regions of the southern hemisphere are of impact origin with varying degrees of obliteration or breakdown due to subsequent geological processes (in scientific literature, such changes in the shape of craters are called obliterations). According to the degree of obliteration, primarily according to the character of the breakdown of the edges or the swells of the slopes, one can judge the age of the crater and the intensity of processes leading to its smoothing out. On the whole, the craters on Mars are smaller than on the Moon or Mercury but significantly deeper than on Venus. The outer slopes of the swells of typical craters have angles of inclination according to ratio to the horizon of about 10°; the interior walls are slanted at 20-25°. As a rule, the bottom of the crater is flat as a result of filling with eroded material.

The predominant shapes of the relief of the northern hemisphere are directly related to active geological processes. Primarily, attention is given to the phenomenon of volcanism -- tremendous shield volcanoes with clearly outlined craters on the apices -- calderas. Such craters are formed with a partial breakdown of the apex of the volcanic cone accompanied by strong eruptions. Four volcanoes in the Farside region are several times larger than those existing on Earth.

The largest volcanic cones are called Mt. Arsiya, Mt. Arkreus, Mt. Pavonis and Mt. Olympus. They reach 500-600 km at the base, rising over the surrounding plains 20-21 km. In relation to the average level of the surface of Mars, the altitude of Arsiya and Akreus is 27 km and Olympus and Pavonis -- 26 km (Figures 28, 31). It is hard to visualize not only the altitudes of these mountains but the diameters of the craters on their summits: about 100 km on Arsiya and 60 km on Olympus. There is not one of the mountain elevations on our planet which can compare with the dimensions actually. For example, the largest volcano Mauna Loa in the Hawaiian Islands is approximately twice as small and in altitude (considering the altitude of the underwater part, 4.5 km) and in the diameter of the base -- its cross

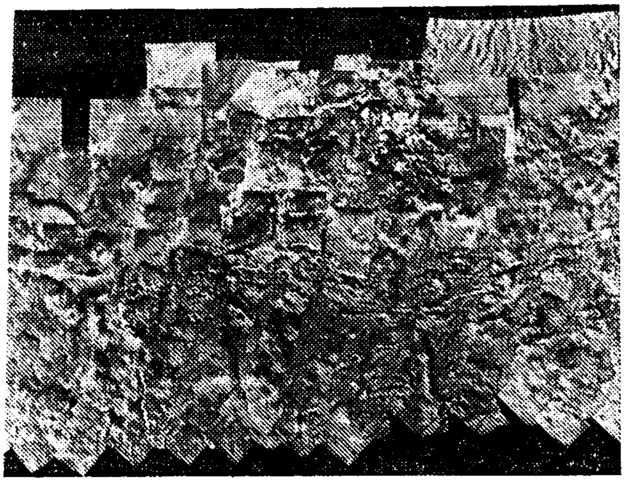

Figure 30. A mosaic of photographs of the surface of Mars transmitted by the Mariner-9. In the left upper section -- volcanic cones on the edges of which Olympus is more than 500 km at the base. Along the equator, the valley of the Mariner extends -- a tremendous canyon with length greater than 4000 km, width 120 km and depth 5-6 km. In the lower part of the photograph in the center, dust tongues are visible in the craters, indicating wind direction.

section of the central crater is a total of 6.5 km. Mt. Olympus is well known to astronomers as the lightest spot observed on the disk of Mars in the middle latitudes identified on the first map as Niks Olympika (the snow of Olympus). The name itself tells us that it is considered an elevation; one could hardly expect, however, that this elevation would be so grandiose in its dimensions. Only in very recent times have we gradually begun, it seems, to become accustomed to such "surprises" on the planets: let us mention the formations which remind us of shield volcanoes on Venus -- in the regions of the Maxwell Mountains and the Lakshmi Plateau or in the Alpha region on the Terra Aphrodite, although altitudes there are much less significant than they are on Mars.

In the regions of Mars where volcanoes are concentrated and craters of impact origin are absent, also there are clearly retained traces of lava flows on the slopes of the mountains which make it possible to assume that the volcanoes were active comparatively recently (according to estimates no more than a few hundreds of millions of years ago). The evidence of volcanism is broadly developed on the planet with well-retained traces of lava flows on the panoramas transmitted from the descent modules of the Viking-2. The landing area on the broad /113
Martian Utopia plain is literally sprinkled with numerous rocks with characteristic fragments and porous surfaces of the pumice type (Figure 32). Similar products of crushing pumice lava into fragments of loose chunks often is encountered on our Earth.

Multiple fractures and ejecta of the Martian crust, the crags which have formed, the graben, the broad ravines with a system of branching canyons are all evidence of the intense tectonic activity (see Figure 30). They reach several kilometers in depth, dozens of kilometers in width, hundreds and even thousands of kilometers in length. For instance, the broad fracture close to the equator extending from west to east is more than 4000 km; this is called the Valley of the Mariner and reminds one of a rift zone on the ocean floor on Earth near its middle ridges. The networks of powerful canyons are often

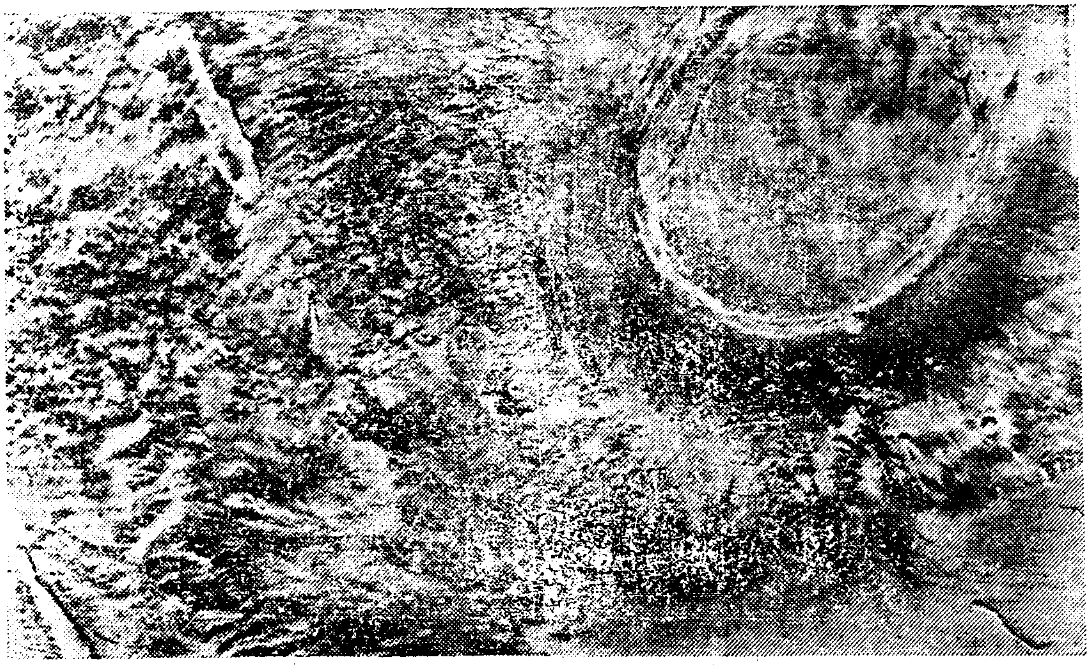

Figure 31. One of the largest volcanic cones on Mars -- Arsiya. Its altitude is 27 km, the diameter of the crater at the apex (caldera) is about 100 km (photographed from the Viking 1).

Figure 32. Panorama of the Martian surface in the landing area of the Viking 2 distinguished by an abundance of porous rock of the pumice type with characteristic fragments, obviously, which are remnants of lava flows.

separated from each other by flat plateaus or mountains with flat summits and steep sides which are made up of simple rock which has withstood destruction. Such rock is called table rock. Obviously, these formations and also the small chains of craters observed from

Earth have created an illusion of Martian "canals" -- one of the best known and attractive hypotheses in the history of astronomy at the end of the nineteenth and in the first half of the twentieth centuries.

It was erroneously believed, right up to transmission of photographs of the surface of Mars from the spacecraft, by the astronomers that these canals actually exist and they moreover, were devoted to unlimited belief in their artificial origin, put forth by a researcher of Mars, the famous American astronomer P. Lowell who studied this exciting problem for more than twenty years of his life. There is no doubt. Even in the time when Lowell worked, there were fierce arguments around the question of the canals and other important astronomers, among them E. Barnard and E. Antoniadi expressed doubt about the very fact of their existence. The well-known Spanish astronomer K. Sola, after the great opposition of Mars in 1909, moreover, supported Lovell who had discovered at that period several hundreds of new canals and wrote: "This opposition, in my opinion, can be looked at as the final blow to the theory of a geometric network of canals." Nevertheless, the arguments continued /115
for several more decades.

What was this about? Why did different groups of highly qualified observers come to directly opposed conclusions? The question here is not actually simple and obviously, is directly related primarily to observation conditions, but also to the special features of the Martian surface. Particularly sharp polemics (with sensational tones usually broadly involving non-specialists, those interfering with the search for truth) made attempts to inscribe a cobweb of more or less ordered thin straight lines on the disk of the planet as activity of intelligent and a highly developed civilization. Moreover, in all fairness one must remember that the word "canaly" was first used in 1859 for designating certain outlines on the surface of Mars; this was done by the Italian astronomer Angelo Secci, who had a completely different idea in this contribution. In translation from the Italian, it means a "strait," or "channel" and has nothing to do with an irrigation system. In the well-known concept, actually this term was conventionally used by another famous Italian astronomer D. Schiaparelli who related this to the discovery of canals during the next great opposition of Mars in 1877.

The strongest argument of opponents to the existence of canals was the well-known fact (which easily can prove each) that as a result of the limited resolution capability of the human eye, the more or less random combining of spots at a large distance, they run together into lines and bands. The same thing can occur during observations with a telescope if its resolution is inadequate to distinguish individual details on the surface. And actually, many times it was reported that when transferring to observations with more powerful instruments and improved conditions of visibility, the straight lines of the canals observed up until then disappeared, or more precisely, flowed into a multiplicity of separate details of irregular shape which were more natural in their form.

Another cause for this was the surface of Mars itself, its relief, the presence of extensive cracks, grooves and other configurations. In truth, attempts to identify the geometric network of canals which had been observed and described and photographed many times with the actual morphology of the surface did not lead to the expected similarity. However, it is impossible to forget that many configurations on Mars have a regular periodic change and some of them can have a more stable character. These are caused by the special features of interaction of the atmosphere with the surface. /116

We have already talked about the fact that as a result of the presence of the atmosphere and the significant effectiveness of erosion on Mars, the craters of meteorite origin are greatly modified. For this reason, a large quantity of dust-sand material was formed which was a characteristic mark of the Martian surface. In the conditions of a water-less medium, this leads to a number of interesting effects. The shift of dust by wind caused by local meteorological and global circulation processes on the planet causes periodic changes in the outlines of the light and dark regions, and the dark regions are systematically warmer than the light regions by several Kelvins. In relatively quiet periods, the fine-grain material basically accumulates in the depressions and with strong winds blows out of them, forming the characteristic light drifts at the edges of the craters, oriented in the direction of the wind. This primary orientation can be retained for a certain period of time also inside the craters where the larger particles of sand and dust begin to predominate. In the photographs taken with high resolution on the bottom of such craters, sand dunes are discovered, reminding one of the barhans of Earth deserts (Figure 33). The traces of the dust deposits are clearly visible also on panoramas transmitted from the Crise region where the landing of the Viking 1 was completed (Figures 34, 35).

The nature of the noticeable "waves of darkness" extending at the beginning of spring from a latitude of approximately 70° to the equator at a rate of about 5 m/s is related to the transfer of dust and the dynamics of seasonal changes in the polar caps; the darkening occurs so that it reaches the equator in less than two Earth months, covering a distance of more than 4000 km. In the summer, when the cap is decreased to minimum dimensions, the dark band reaches the latitude 40° in the opposite hemisphere and in the fall with the beginning of an increase in the cap, rapidly moves backward and the "sea" becomes lighter. In the pertinent theory of Lovell, this was explained as the spring awakening and the rapid extension of vegetation along the living arteries -- the canals filled with water with the beginning of thaw of the polar caps. This in truth grandiose irrigation system of highly developed Martians naturally was considered as the only intelligent means to counteract the severe nature of the planet where the landscape was predominantly desert and water in dry conditions was less dense than on Earth; the atmosphere rapidly evaporates. The dark /118

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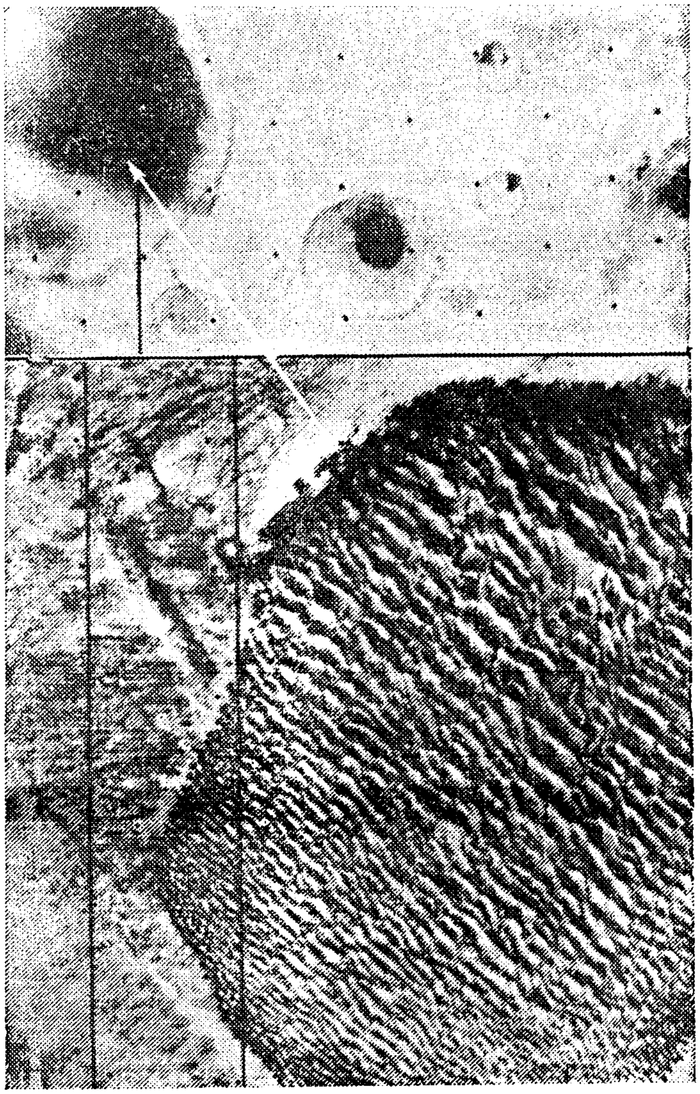

Figure 33. Formation of sand dunes inside the Martian craters showing as dark spots on the photographs with low resolution (from above). A cross section of the crater shown in a larger scale below, 150 km, distance between the dunes about 1 km (photograph from the Mariner 9).

strips of Lovell's canals involved not water but vegetation similar to that observed, let us say, from Mars in the region of the Sahara on Earth and the Martians would look at the Nile and the colorful valley irrigated by it on a yellow background of desert.

Fortunately, the actuality as often happens was much more prosaic though from the physical point of view, /119 exceptionally interesting. This involves the fact that the seasonal restructuring of the circulation system leads to a transfer by wind blowing form the colder polar regions, of thin-grained material having increased reflective capability as a result of which relatively dark sections of the surface were detected. A large quantity of light, loose material accumulated in large almost circular basins of the Ellada type, smooth out the irregularities of the surface on their bottom which during observations from Earth creates the impression of light plains.

The abundance and intense movement of dust explains why no sort of definite interaction of the irregularities of the terrain where the reflected properties (albedo) of the surface of Mars was observed; and also why /120 for the majority of regions of the planet a small density of soil is characteristic. The albedo of the surface undergoes significant changes and many characteristics of the relief are simply masked.

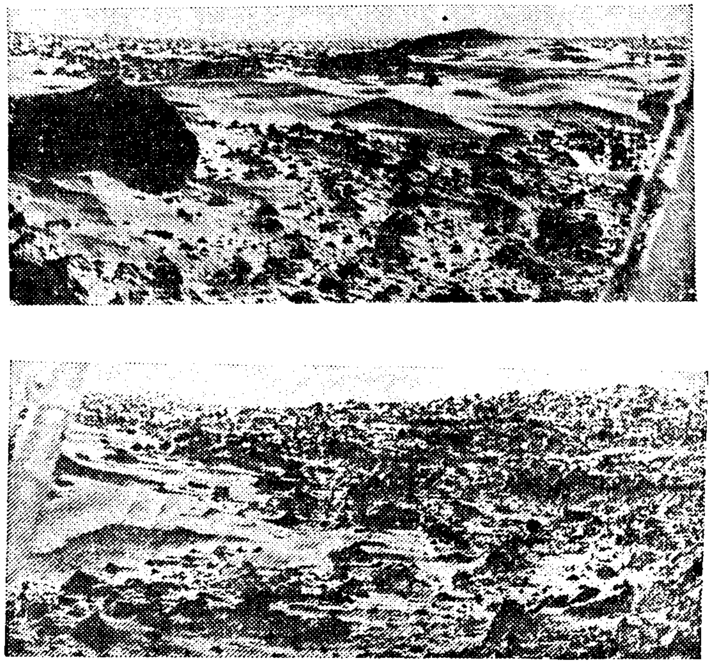

Figure 34. Panorama of the Martian surface in the landing area of the Viking 1. The sand dunes and sharp-angled rocks are visible.

Sometimes, powerful dust vortices occur purposely called "dust devils." The situation acquires a global character in the period of dust storms -- a grandiose natural phenomenon periodically encompassing the entire planet. The dust during a storm rises to an altitude of 10 or more kilometers so that the only things protruding from this solid film are the summits of the largest volcanoes and all of the remaining surface becomes a level yellow background without any kind of detail.

The Rivers and Glaciers on Mars

The bombardment of meteorites, the global tectonics, broadly developed volcanism and wind erosion (it is often called eolian, named for the source of winds in ancient Greek mythology, Eola) -- are not single active processes which have formed the surface of Mars. In the photographs transmitted by the spacecraft showing the long branching valleys extending for hundreds of kilometers, in their morphology one is reminded of dry channels of Earth rivers, smoothed out stream beds and other characteristic configurations which are also evidence of water and glaciers (fluvial-glacial) erosion (Figures 36, 37). This leads to the hypothesis that in a certain period of Martian history, the surface of the planet was furrowed by flows of water formed by meandering channels (named for the wandering river Meander in Asia Minor) with a developed system of inflow and moved by glaciers. They form in regions of an ice drift with flow around craters, drop-shaped islands and other forms of breakdown of mountain rock and ploughing up of the surface, or, as they say, exaration. For example, in Figure 37, traces of strong smoothing are clearly obvious most probably caused by glaciation but possibly, water played a certain role here with its flow forming channels between the local compacted material of the surface. The greatest compaction, obviously, involved craters of impact origin, a cross section of which is shown in Figure 37 reaching 10-15 km.

The fact of gradations in altitude in the direction of flow of /121
ancient rivers from source to mouth is evidence of the water origin of the numerous channels retained whose total number is estimated to be several tens of thousands. Part of these channels extend between sections of the craters' surfaces which have been deepened, obviously,

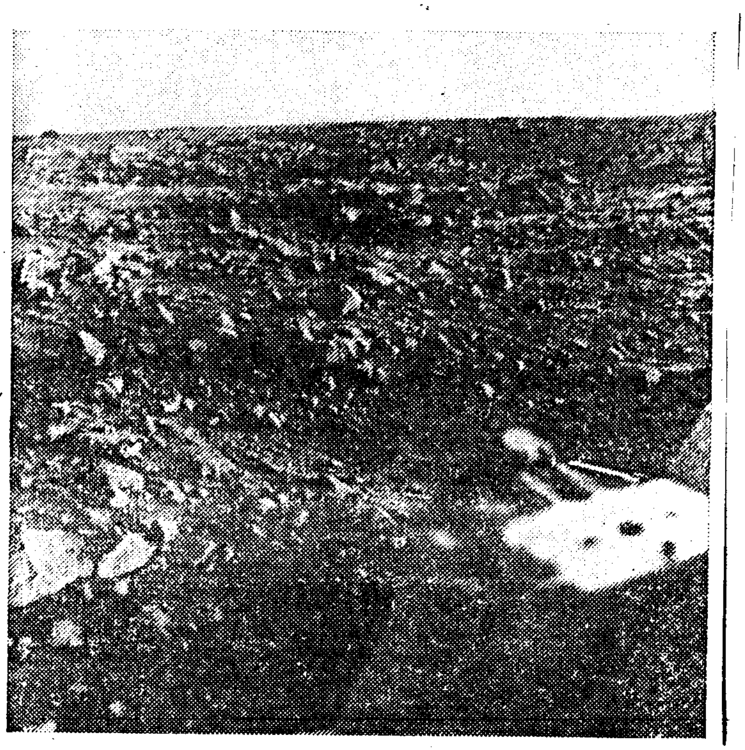

Figure 35. Panorama of the surface of Mars in the Crise region 15 minutes before sunset. In the front -- a depression; dimensions of the largest rocks less than 30 cm (photograph from the Viking 1).

acting as local water reservoirs. This is clearly visible in Figure 36 where the extent of the channels between craters in the Crise region reaches more than 300 km with the drop in altitude about 3 km.

How ancient are the river channels which are trough-shaped (glacial) valleys left by glaciers and certain other formations which are clear evidence of the presence of water on Mars? To what period (or periods) of Martian history do these events belong? This problem, like a problem of general water reserves on Mars is directly related to the paleoclimate of the planet, the chemical composition and evolution of its atmosphere about which we will talk separately. Now we shall only note that the precision of many of the fluvial-glacial forms which are retained, the absence of traces of /122 their burial by later strata all indicate the relatively recent origin within limits of the last billion years. But the configuration of certain of the troughs on the slopes of the elevations can even presuppose that sometime rain occurred -- situations which are completely impossible in the present conditions on Mars with the low content of water vapor in the atmosphere and the very low atmospheric pressure on the surface at which water in liquid form could hardly be maintained and would rapidly evaporate.

Starting from the general geochemical principles about the release of water from planetary interiors, now tied to the clearly pronounced signs of volcanic activity on all the planets of the Earth group, many scientists even recently have put forward the idea that the main water mass on Mars is concentrated in the surface layer of ancient frozen ground, particularly in the layers of permafrost and in /123 the large plain basins of the Ellada type. Also, this does not exclude the possibility that due to an ordinary geothermal temperature gradient within these basins, under a layer of ice, the temperature could have been adequate for storing water in a liquid state. This supposition was put forward by Soviet scientist A. I. Lebedinskiy and V. D. Davydov.

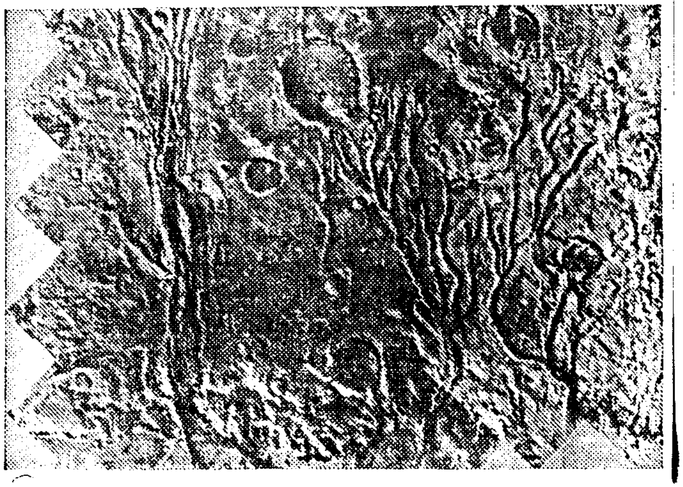

Figure 36. The arroyos on the surface of Mars, evidence of ancient rivers with well developed dendrite system of channels; dimensions of the region in the photograph 300X400 km, slope of the surface from the source to the mouth 2-3 km (photographed from the Viking 1).

A number of details are active proof in favor of concepts about the existence on Mars of broad regions of permanent frozen ground. These, in particular, include specific valleys with outcropping on their slopes of internal bubbles of the karst type on Earth (Figure 38). It is very probable that they were formed with a primary outcropping and subsequent sublimation of the ice layers (a lens) and that a fair number of such reservoirs covered with loose soil were retained on Mars. Territories with chaotic relief which contain chaotically broken blocks of rock have approximately the same /124
nature as those encountered on the planet. Most probably they were formed due to settling of exterior layers as a result of a shift in the surface material. Specific shapes of ejecta on the outer slopes of certain craters which remind one of snow avalanches are evidences of regions of permanent frozen ground (Figure 39). The origin of such configurations which do not have analogues on other planets can be explained by melting of the surface ice under the impact of the meteorite and the flow of the contaminated waters along the slope of the crater formed. /125

The broad field of permanent frozen ground on Mars gave us the basis for assuming the presence on its surface of igneous rock of the palagonite type -- a yellow-brown glass-like mineral (or dark brown) encountered on Earth in basalt, diabase and tuff, primarily in the polar regions (tundra of the Great Earth, Iceland, the Terra Franz Joseph, the Antarctica). Palagonites are formed during interaction of magma with water or with eruption of it through the ice layer. They are rich in iron and poor in silicon which once again is confirmed by analysis of the element composition of rock on the surface of Mars. Moreover, due to the low atmospheric pressure, Martian palagonites can differ from those of Earth in the lower content of volatile elements and the less strong structure.

As we saw, under certain conditions, when due to the incidence of a meteorite, volcanic eruption or another local geothermal sources results in melting of the ice, on the surface of Mars, there could form (or be hidden) water reservoirs. Then naturally the question arises as to what happens to them later on. It is inadequate to simply say (as we have already suggested recalling possible rain flows

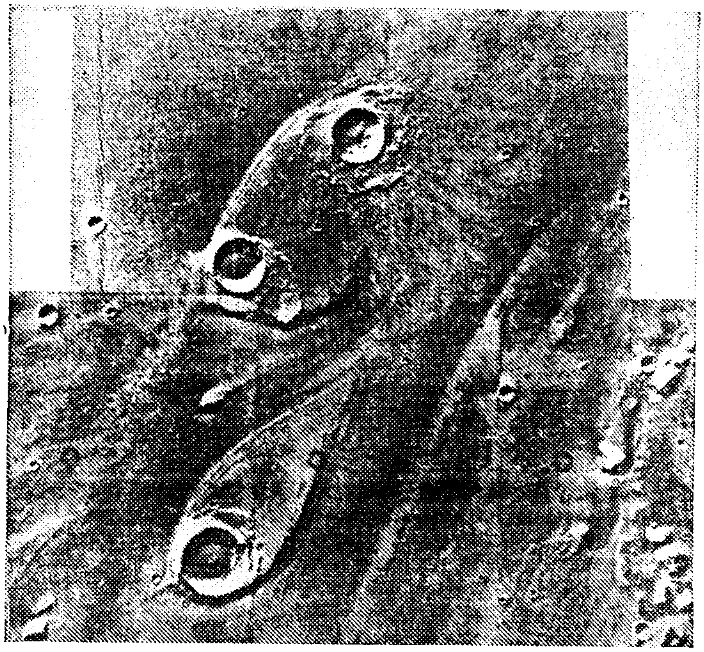

Figure 37. Smoothed hollows of the Martian surface with characteristic drop-shaped islands near the craters, probably left by moving glaciers and possibly with the participation of streams of water; dimensions of the craters 10-15 km (photographs from the Viking 1).

in the early history of Mars) that in the conditions of a rarefied atmosphere with the average temperature on the surface -50°C (223 K) the water evaporates or it is converted back into ice. The problem is that it must be studied in detail, quantitatively, not qualitatively.

This has been done by the well-known American paleontologist C. Sagan along with D. Wallace. Their calculations showed that evaporation actually very rapidly practically ceased due to the manifestation on the liquid surface of the ice cover reaching a thickness of at least a meter. The lower the pressure of the atmosphere the more intense is the evaporation and the stronger the cooling of the surface due to the release of hidden heat of evaporation and this means the thickness of the layer of ice formed. This inherent type of "feedback" is very effective, but the rate of sublimation from the surface of the ice, depending on the value of solar energy coming to Mars (insolation), the pressure and dynamic processes (wind and free convection) in the atmosphere, is insignificant. It is at least /126
several magnitudes smaller than the rate of evaporation from the surface of Earth rivers. In the final analysis, the thickness of the ice cover on the average must reach 10-30 m, which corresponds to conditions of equilibrium between its growth and sublimation. As is well known, the ice is a good heat-insulating material and at the same time, it is adequately transparent for the solar rays which partially penetrate through it and are absorbed in the water layer itself. Along with the latent heat which is released from the melt on the lower surface of the ice, this prevents further freezing of the reservoir providing storage in it of liquid water.

All of this led the authors to an interesting hypothesis about the existence on Mars not only of broad reservoirs (lakes) under a layer of permanently frozen ground but also the continuing flow of rivers today squeezed by the ice shield only from the surface! And if this is actually so, then it is natural to propose that the formation

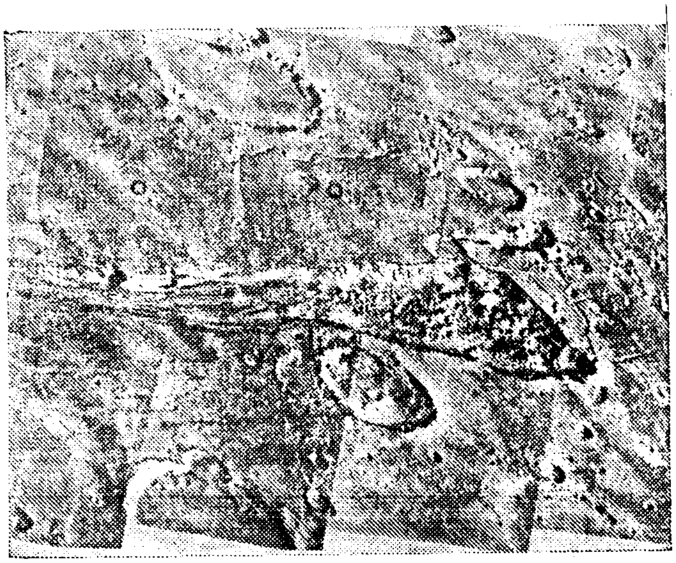

Figure 38. An example of formation of a valley on the Martian surface obviously was due to melting of the near-surface ice and reminds one of the karst phenomenon on Earth. Dimensions of the field in the photograph are 300X300 km (Viking 1 photograph).

of at least some of the channels observed occurred continuously. It would be possible to say that the majority of frozen rivers, probably, are covered by sand deposits and that in this case, both the rate of sublimation and the quantity of heat penetrating inside is sharply decreased and that the condition of equilibrium is shifted. Actually, in such areas, probably the ice cover is thick; however, as a result of regular movement of the dust, the conditions can change.

An opposite effect must be observed when increasing insolation leading to a decrease in the thickness of the ice cover. In certain sections of the surface where freezing was complete, it is possible that under the layer of ice, liquid water appears so that this layer essentially becomes an iceberg. Such a situation, in particular, could occur in the near-polar regions as a result of periodic change in the slope of the axis of rotation of Mars relative to the plane of ecliptics which we talked about in the preceding section. It is tempting to relate the special features of morphology of the surface here to this hypothesis. When the southern polar cap melts (which the present era is still an entity as a result of noticeable eccentricity of the orbit of the planet) layers are revealed which were formed by sedimentary rock. In these concentrated strata around the pole, there are several hundreds of layers going from one to dozens of meters which have the form of a terrace. These /127 structures can be explained by the cyclic activity of glaciers of the polar cap when changing the slope of the axis of the planet on which the intensity of their melting strongly depends. It is assumed that sequential processes of depositing precipitation during of glaciers with the formation of "water pillows" and icebergs partially smoothed off with their shifting over the unevenness of the terrain have occurred for hundreds of thousands of years (see Figure 6).

The white polar caps of Mars are one of the most noticeable features on the disk of the planet which are easily observed in a telescope. In a similar way, one can isolate the polar regions of Earth during observation, from Mars, particularly the broad snow-covered expanse of the northern hemisphere in winter extending to the middle latitudes. However, up until recent times, there has been argument about what the Martian cap consists of -- the ordinary water ice or a solid carbon dioxide ("dry ice"). The latter hypothesis

Figure 39. Impure ejecta from craters frozen on the slopes. Their formation, probably, is related to melting of the subsurface during impact of the meteorites. The diameter of the crater is 25 km and inside it a characteristic central piece is visible, formed during the strong impact (photographs from Viking 1).

involves the fact that at the poles one notes a very low temperature of the surface on Mars, 148 K = -125°C. And this once more corresponds to the freezing temperature of carbon dioxide of which the Martian atmosphere primarily consists. Measurements from spacecraft showed that there have generally been defenders of this and other hypotheses; however, in the main mass, the polar caps are formed of ordinary ice. It would seem that the intensive growth of the caps occurs in the period from the beginning of the Martian fall to the beginning of spring in the appropriate hemisphere due to condensation of carbon dioxide from the atmosphere. Then a layer of dry ice forms with a thickness of a few centimeters rapidly disappearing in the onset of spring. After this, the part unmelted in the summer remains, having a temperature of about -70°C (203 K), that is, significantly exceeding the temperature of freezing of carbon dioxide. This consists basically of ordinary ice covered, like the underlying surface, with a layer of carbon dioxide in the wintertime.

It is very probable that the caps contain also broad inclusions of gaseous hydrates -- the so-called clathrates which are compounds which form during introduction of molecules of carbon dioxide gas (or /128
other gases) into a bubble of a crystal structure of water ice. In exterior appearance, they remind one of fresh snow and are well known primarily as a byproduct when obtaining natural gas. We note that such compounds can be introduced into the composition of the nucleus of a comet along with ordinary ice and certain other solid components (CH_3CN, HCN et al). On Mars, the clathrates, possibly, form in the

Figure 40. An example of the formation of a "white rock" at the bottom of a Martian crater with diameter 93 km located approximately 400 km to the south of the equator. The dimensions of the formations 14X18 km, resolution on the photograph about 150 m. The nature of this and other similar formations continue to remain under discussion inasmuch as the snow or ice is excluded according to the conditions of thermal equilibrium (Viking 1 photograph).

middle latitudes at night, especially inside depressions and craters as was noted on the Viking photographic panoramas. With the rise of the Sun, the condensate rapidly sublimates. The measured temperatures of the atmosphere, once more, agree well with the phase transition during formation and disappearance of all CO_2 clathrates.

Nevertheless, final identification still has not been made and therefore both these and other broad white formations on the bottom of certain craters observed in the photographs from orbital vehicles, are still conventionally called "white rock" (Figure 40).

The thickness of the northern polar cap can be compared with the thickness of the ice shell of the Antarctic, reaching 4.3 km and the ratio of area of this "armor" for the area of the Earth's surface is less than the unmelted part of the cap for the area of the surface of Mars. But the ice in Antarctica contains more than 90% of the reserve of all fresh water on Earth and it is impossible to exclude the idea that such a reservoir exists on Mars.

Everything related to water on Mars is not just extremely interesting but also it is extremely important for understanding the common problems of planetary evolution. Unfortunately, we can judge the proposed water reservoirs only by indirect data, there is no direct evidence of their existence as yet. These proofs could be produced only by experiments. What experiments? Well, we don't expect dozens or hundreds of thousands of years in calculations for possible climatic changes on the planet! It is possible to put down a self-propelled vehicle on the surface (a Marsokhod) equipped with mechanisms for drilling and conducting "detective work" (a type of excavator). It must be capable of covering great distances, including sections with difficult terrain and loose soil. It is impossible, however, to forget that in distinction from the lunokhods, the possibilities of controlling such a craft from Earth would be limited: in order to receive information from them about the environment, analyze it and transmit commands, as to where and how to proceed, it would be necessary to do this not in seconds but in dozens of minutes. If we make an analogy with walking, then the situation could be similar to standing on first one leg and then the other for approximately half an hour waiting for a signal so that one could put down the other foot. In the opposite case, without confirmation of the safety of the selected route, the vehicle, for example, could be flipped over. Consequently, to a significant degree it must be autonomous, self-controlling, equipped with a so-called adaptive system (for example, a three-coordinate laser range finder and an onboard computer), in order to rapidly evaluate the special features of the terrain and select the direction for the safest movement. Designing such a vehicle with a modern level of development of engineering is possible although it would require great expense. /129

Another way is to attempt to make observations from the Mars artificial satellite; however, not the usual passive observations which would add little to the well-known information but one accompanied by active action on the surface of the planet. It would be easy, for example, to realize an "artificial meteorite bombardment" -- ejection into the region of proposed water (ice) reservoirs of a capsule with an explosive substance and simultaneous photographing of the dynamics of the phenomena which would occur on the surface along with a set of other measurements in optical and radio range wavelengths. This would make it possible to detect the presence of water in the case of a short-term manifestation on the surface. /130

Of course, possibly there are some other methods; their detailed consideration and comparison, however, were not considered in our task.

Phobos and Deimos

As we have already discussed, the most important criterion for evaluating age of these or other structures on the surface of the planet is the number of craters of impact origin depending on their dimensions and degree of breakdown. However, in conditions of strong erosion, it is difficult to establish the initial intensity of craters on Mars. This density of craters in certain sections can be partially related to the latest volcanic activity and not only to the age of ancient forms of terrain. In the sections of the surface with the greatest number of craters, the number of craters and their distribution by dimension are comparable to the degree of saturation of the lunar surface at the same time that in other sections they are almost absent (see Figure 4).

The number of impacts which the surface of all planets are subjected to in geological survey is a type of control number for obtaining a comparative evaluation and this makes it possible to study the surface of the satellites of Mars -- Phobos (Figure 41) and Deimos (Figure 42). Inasmuch as the satellites are devoid of atmosphere and are located in the same region of the solar system as the planet

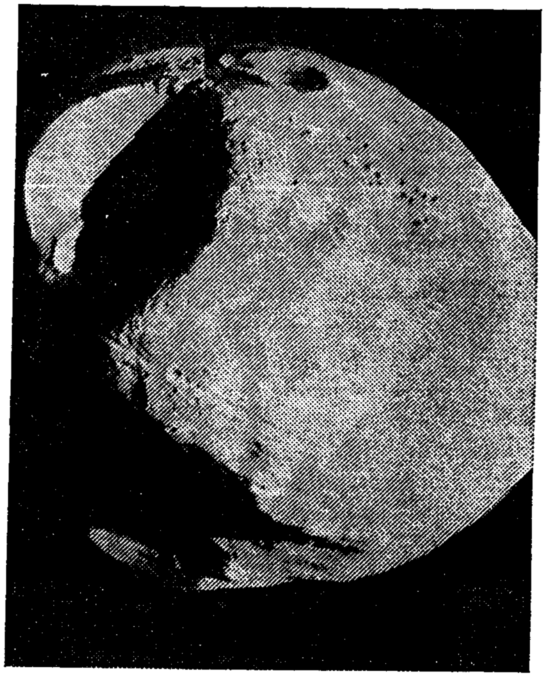

Figure 41. The closest Mars satellite -- Phobos. The side constantly turned toward Mars was photographed. On the left on top is the largest crater Stickney with diameter 10 km. Below one notes lateral furrows, probably these are cracks which occurred during impact by a meteorite forming this crater (Viking 1 photograph).

itself, being either the final product of accretion in the initial phase of evolution of Mars or more probably captured in a later stage by asteroids), such a comparison appears to be correct. It is evidence of the very high effectiveness of processes of erosion on Mars inasmuch as the saturation with craters of the /131
surface of the satellites is higher.

It is curious that the satellites of Mars have a very narrow reflective capability (albedo less than 5%), so that possibly they are the darkest objects among the asteroids in the solar system. From the materials which have such a low albedo, the most probable are carbonaceous chondrites which are a non-dense dark carbonaceous substance rich in hydrated silicates, gases, and even organic compounds. They form a small group among the usual chondrites -- the most widespread class of rock meteorites containing the largest number of light volatile /132
elements. The hypothesis about the carbonaceous chondrites and the relatively small density of satellites (about 2 g/cm^3) does not contradict the most probable model of their internal structure according to which the loose material was formed only int the outer layers surrounding a denser nucleus. Obviously, their surface is covered with a layer of dust as a result of intense meteorite bombardment and the surface layer reminds one of the lunar regolith. As the photographs obtained from the Mariner 9 and the Vikings at a near distance have shown, the dust has filled the crater on Deimos in cross section for approximately 50 m as a result of slipping along the slopes. Due to the low force of gravity and, consequently, the low rate of velocity which is called the second cosmic velocity (for Phobos it has a total of about 13 m/s and for Deimos about 8 m/s) one can expect an increased density of /133
dust particles along the orbit of the satellites -- formations of a type of dust tore.

On the photograph of the surface of Deimos obtained with the highest resolution (see Figure 42), separate blocks of irregular shape with cross section of dozens of meters can be differentiated (that is, their dimensions are that of a small house), and obviously one can see traces of ejecta from the craters during impact of the meteorite or

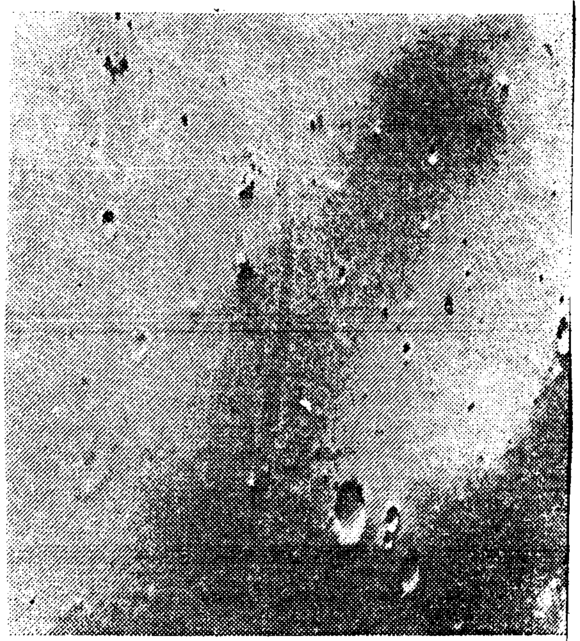

Figure 42. Surface of Deimos taken with a resolution of several meters. A large number of small craters are visible with diameter 50-100 m, separate rocks with dimensions of a small house (Viking 2 photograph).

its fragments. A most impressive feature of the surface of Phobos (see Figure 41) are the linear structures of the furrow or trough type which are oriented approximately perpendicular to the axis directed toward Mars. For an explanation of the origin of these structures, different hypotheses have been proposed. The hypothesis about the tidal effects which are significantly stronger than those on Earth from the Moon which leads to the formation of "folds" seem to be completely correct. An attempt has been made to connect the troughs with erosion of the material of different density on the surface of a larger body whose fragments could be Phobos and the subsequent deposit of loose material. An original idea has been put forward about the occurrence of cracks due to inner stresses during a slowdown in the process of hypothetical capture of this body from a band of asteroids at a comparatively close orbit around Mars.

A thorough study of the images of D. Veverka and other scientists shows, in our view, the most convincing proof in favor of the hypothesis that it is more the cracks and not the folds and not the remaining types of erosion although in their morphology they are fairly complex, and obviously as a result of interaction with surface regolith. However, the cause of these formations can vary. It is impossible, in particular, to exclude the fact that the large Stickney crater with diameter about 10 km visible in the left upper part of Figure 41 and the furrows on the surface of Phobos occurred in one and the same process. Actually, the larger more clearly pronounced cracks which have a width from 100 to 200 m and depth from 10 to 20 m are found close to the crater which formed from impact of a large meteorite -- events almost catastrophic for a small body although they would partially consist of carbonaceous chondrite (material which is weak in its mechanical strength) hardly resulting in its breakdown. On the opposite side of the crater, the cracks are smaller and the largest is directly adjacent to the Stickney crater and has a width of 700 m and depth 90 m! These dimensions are tremendous if we /134
remember that the maximum cross section of Phobos is a total of 27 km and the minimum of 19 km.

Starting with the rate of crater formation on heavenly bodies in the region of orbit of Mars (here it is approximately twice as high as, for example, in the region of the Earth-Moon) and the density of craters on Phobos an age of furrows is estimated at 3.4 billion years. At the very least, it is no less than 1 billion years if one assumes that for any reason the intensity of bombardment by large meteorites close to the asteroid band was similarly high. Was this a singular "almost catastrophic" event in the history of the satellites on Mars? This we don't know, although it is fully reasonable to assume that other large catastrophes could have occurred and that the satellites existing now actually were a fragment of larger related bodies -- a corrected point of the erosion hypothesis for formation of linear structures on the surface of Phobos. Truly, the overall photography from the Vikings did not result in detecting other "fragments" with dimensions more than approximately 1 km; however, one must not forget that the area of space covered by the observers was limited. One would have to consider that for a period of a billion years complex evolution of their orbits could occur.

Satellites of the Planet Giants and Pluto

Thus, we have become familiar in general terms with the family of planets close to our heavenly body. Among the other families located beyond the asteroid band, not one of the four large planets possesses a solid surface in the ordinary meaning of the word which we have already mentioned above. As to Pluto, we have seen that it is impossible in any way to relate it to the large planets either in dimension or in a number of other characteristics. More likely it reminds one of a large asteroid (or a system of two asteroids) and therefore some of the scientists in general are not inclined to count it as a planet. But the family itself of large planets includes many solid bodies. These are their satellites encompassing a broad range of dimensions from those comparable to the planets of the Earth group /135
to small asteroids (see Table 2).

Unfortunately, the evidence about these bodies based on ground observations up until recently were very limited. The position was rarely changed after flights of the Voyager spacecraft through the Jupiter and Saturn systems. We will discuss these results in more detail in other sections. Today, first of all, little is known about the most outer satellites of Jupiter and Saturn which have the greatest inclination and eccentricities in orbit and also about the satellites of Uranus and Neptune. Approximately four of the large family of satellites of Jupiter and also Phoebe -- the Saturn satellite, are found in very distant orbits, turning around their own planets not in a forward direction but in a reverse direction. Already the fact itself definitely indicates that these satellites, probably, are captured asteroids which have an incorrect shape and that the basic characteristics of their surfaces have not undergone noticeable changes after capture (an exception, possibly, is more intense bombardment when remaining in the environs of a large gravitational body). At the same time, the nature of other large satellites particularly close to a planet most often is different, closely related to the period of formation of the planet itself.

It is possible to propose that with a very low temperature of condensation in the external regions of the solar system and with

C-2

comparatively small dimensions of these bodies, a significant part of the component matter is water, ammonia and methane ice which, in many cases, was detected on the surface. The most probable is the presence of water ice as a result of its large content in the solar system and also its higher stability in comparison with ammonia and methane ice.

Just what is it that is observed? The water ice actually was detected on three of the four Galilean satellites of Jupiter and on six satellites of Saturn. The spectra of reflection of Galilean satellites in comparison with the spectrum of ice made from H_2O is basic primarily for this conclusion; it showed the characteristic signs of ice absorption is particularly pronounced in the spectra of Europa and Ganymede and to a much lesser degree they are apparent on Callisto, and on Io they are generally absent. This has led to a concept of significant differences in the surfaces of these bodies and /134
different paths of their thermal evolution.

But the results of ground astronomical observations noted an almost analogous situation on the satellites of Saturn. These observations led to a conclusion (as we will soon prove -- more basic) about the fact that surfaces covered with water ice or even almost a complete ice composition have larger satellites within the orbit of Titan -- Mimas, Enceladus,Tephiya, Dione, Rhea. Later Hyperion was added to this family. Less definite conclusions can be drawn relative to Yapeta which was discovered back in the seventeenth century by D. Cassini who detected an amazing feature: one of its sides in the direction of movement in orbit has a reflection capability which is several times higher than the opposite side. Much later, the surface on the light side in its composition was identical to the water ice and the reflection from the dark side was as low as it is for coal dust.

Unfortunately, nothing is known yet about the surface of this largest satellite of Saturn -- Titan, but in dimensions it is larger than Mercury. This is explained by the fact that the study of reflecting properties of its surface changes the atmosphere. They assumed that the surface of Titan could consist of water or methane ice. A hypothesis was put forward according to which it could be covered with a thick organic mass. The basis of the latter was results of laboratory studies showing that in the methane-hydrogen atmospheres, under the effect of ultraviolet radiation, complex hydrocarbons are formed such as ethane, ethylene and acetylene. But is this adequate for long-lasting conclusions right up to the inverse images of the primary form of living matter? And here how can we not remember the existence back in the 1950's of concepts close to this about the surface of Venus: it was assumed that there was an abundance of hydrocarbons, a sea of petroleum and even actual vegetation. Unfortunately, the reality has once more dashed these exotic expectations; will Titan be an exception as it was established not long ago that it has a cold nitrogen atmosphere?

Even at the beginning of the 1980's, thanks to the possibilities discovered of obtaining high-quality spectra in the near infrared field using a large infrared telescope on the Mauna Kea Observatory, reliable information was successfully obtained about the satellites of Uranus. The presence of characteristic absorption bands in the interval of wavelengths 1.5-2.5 km has made it possible for the American astronomers R. Brown and D. Cruikshank to conclude that the surfaces of Ariel, Titania, Oberon and Umbriel also were made up of water ice. Then it was discovered that a purely ice surface exists only on Ariel at the same time that in the spectra of the others there are signs of other components partially covered in the ice or mixed with the ice. Such a component could be silicate rock. On the whole, we are looking at a certain principle: the farther the satellite is from the planet, the larger the quantity of admixtures. In character of reflection, the degree of "contamination" of the ice surfaces of the satellites of Uranus on the average is higher than, for example, the surface of Ganymede but lower than the dark side of Yapeta. As to satellites of Neptune, what kind of proof is there of the presence of water or condensation of ammonia or methane ice formed at even lower temperatures still unfound. This is a question for future studies requiring further improvement in methods and instruments for conducting these very difficult observations. /137

In distinction from the satellites of the planet-giants, on Pluto there are identical spectral signs of a methane condensate. According to the results of narrow-band photometery, the ratio of intensity of reflection in the two spectral fields, in one of which bands of absorption of water and ammonia ice are located and then the other -- a strong band of absorption of methane ice, prove to equal 1.6. If we take pure methane ice and take those spectra in the laboratory, then the ratio appears only somewhat larger at the same time that for the satellites of giants with signs of water ice, on the surface this ratio is significantly smaller than 1. This fact is a fairly strong argument in favor of the presence of methane. The discovery of methane gas on Pluto changes the concepts existing up to recent times about its surface formed of rock changing toward more real hypotheses about the extensive ice layer covering it.

Surfaces of the Galilean Satellites of Jupiter and Amalthea

After the flybys of the Voyager around Jupiter, we found out much that was new and interesting about Galilean satellites of Jupiter. Finally, it has become possible to see their surfaces (Figure 43). Three new small satellites were discovered, two of which called Adrastea and Metis are found closest to the planet (see Table 2) and consequently, are considered closest to the Amalthea satellite of Jupiter (Figure 44) shifted to third place and from fifth to eighth in the Galilean satellites. /138

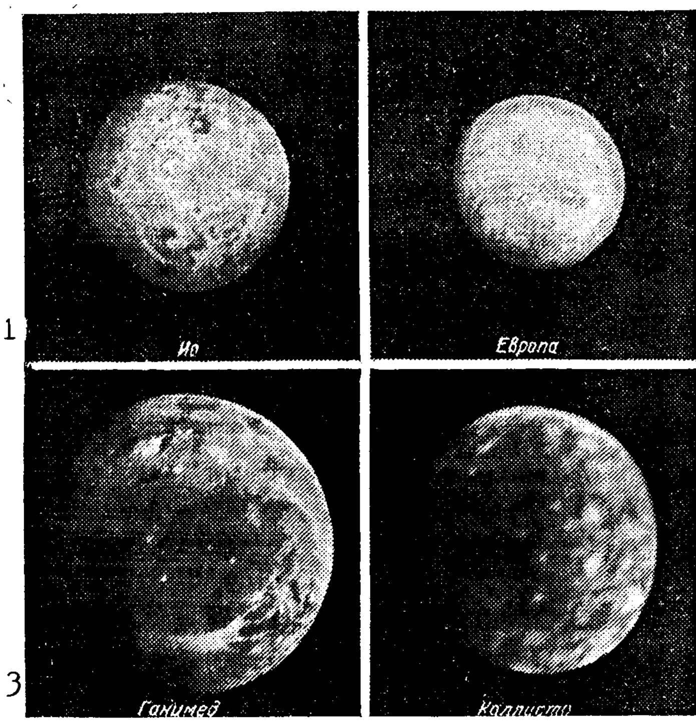

Figure 43. Galilean satellites of Jupiter. The maximum contrasts occur on the surface of Io, the minimum on Europa. In both these satellites, there is the highest albedo. The darkest object is Callisto. The reflecting characteristics are determined by different properties of the surfaces of these bodies (Voyager 1 photographs).
Key: 1. Io; 2. Europa;
3. Ganymede; 4. Callisto.

In its dimensions and position, the Galilean /139 satellites can be similar to a model of the inner field of the solar system where one finds planets of the Earth group. However, these bodies which have unique properties of the surfaces differ strongly from the Earth planets in a whole series of characteristics.

The most convincing was the first of the families of Galilean satellites -- Io, on which many active volcanoes are observed (Figure 45). For several hours of flight of the two Voyagers, several inversions were observed with powerful volcanic ejections and then six of the seven volcanoes recorded by the first craft continued to operate for four months afterwards during the flight of a second craft. The largest eruption with traces of igneous flows of lava and volcanic deposits, in form reminding one of the imprint of a cow's hoof is visible a little to the right and below center in Figure 45. Three large inversions are clearly outlined on the edges of the disk of Io (Figure 46). The height of the powerful ejecta on the right comprises almost 300 km and it is easy to consider that for this it is necessary that the velocity at the output of the volcanic vent is about 1 km/s! This by many times exceeds the velocity and altitude of ejecta during eruptions of volcanoes on Earth, although during observations from space, also one sees events /140
which are no less impressive as is seen in Figure 46 below on an example of the eruption of the Etna Volcano on the island of Sicily. It is explained by the fact that primarily in distinction from Earth, Io has a very rarefied atmosphere and therefore the products of eruption accelerate due to expansion of gas in a vacuum. Then the focus of the eruptions can be located at a very shallow depth.

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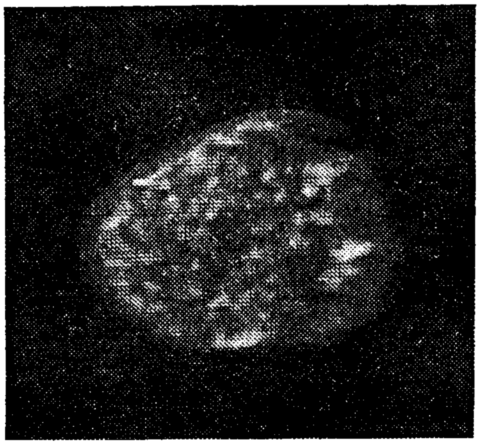

Figure 44. The Amalthea satellite of Jupiter, its dimensions 270X170X150 km. Its incorrect shape and low reflecting capability remind one of an asteroid; the surface is craterized (Voyager-1 photograph).

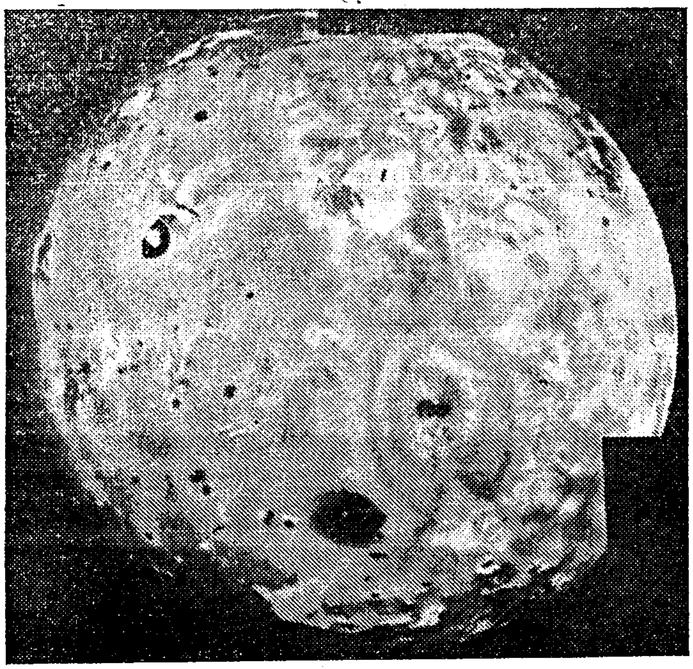

Figure 45. The surface of Io with characteristic traces of volcanic activity (mosaic from four photographs taken from the Voyager 1).

What are the products of eruption which are directly related to the structure and color of the surface? The spectra of reflection of Io in which one detects signs of water or water ice contain, moreover, precise signs of sulfur and its compounds (this is apparent primarily as a strong decrease in reflection in the blue and ultraviolet parts of the spectrum). The emission spectra radiated by the matter in the environs of the orbit of Io favor sulfur and naturally it is assumed that the satellite is a source of this substance put out by powerful volcanic ejecta. It is well known that sulfur in the form of sulfur dioxide (anhydride) SO_2 and hydrogen sulfide H_2S is one of the main products of volcanic eruptions for us on Earth. Taking into consideration these and a number of other expressions, all of the scientists have come to the opinion that sulfur itself played and continues to play a definite role in the geology of Io and evolution of the surface of this satellite. /142

A large quantity of sulfur can be accumulated in a geological epoch in the surface layer above a silicate crust. The thickness of this layer is estimated at 3-4 to 20-30 km. Rising from the depths, the liquid magma due to density larger than that of sulfur hardly reaches the surface (similarly to a majority of eruptions of underwater volcanoes on Earth) and interacting with deposits of sulfur and sulfurous anhydride results in their evaporation. The expanding gas erupts into space, takings flows of liquid sulfur with it. When

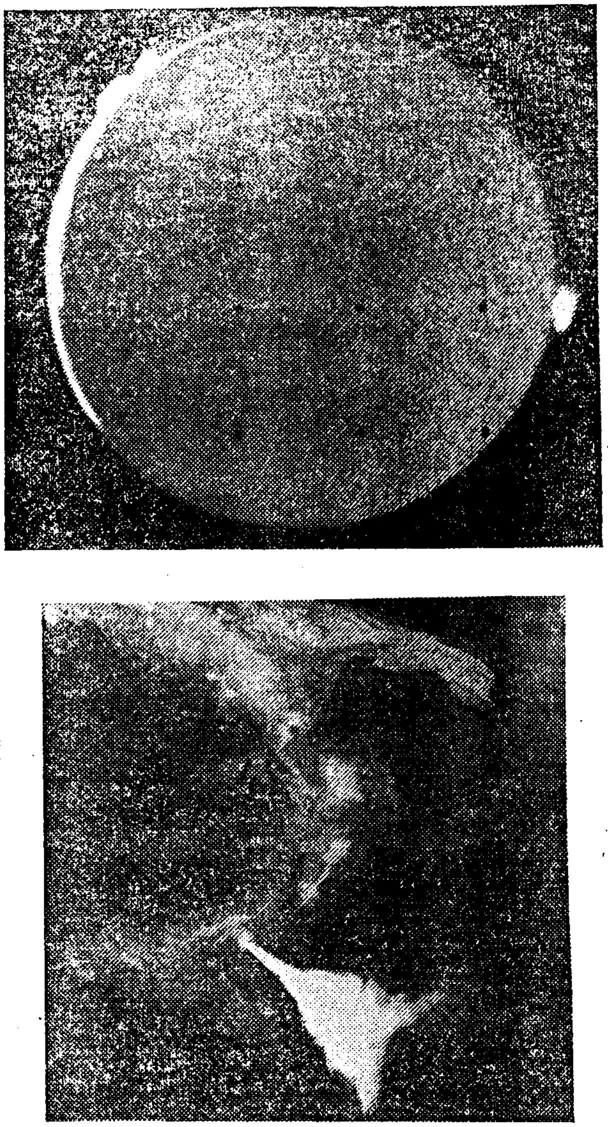

Figure 46. On top -- the eruption of volcanoes on Io; altitude of the ejecta reaches 200 km (photographs from the Voyager 2). Below (for comparison) -- eruption of the largest volcano in Europe, Mount Etna (on the island of Sicily). The photograph was made from the Tyros satellite on August 4, 1979, in the infrared field of the spectrum. The extent of the cloud of gases and ashes is about 200 km, altitude of the ejecta about 20 km.

cooling the sulfur and the sulfurous anhydride, they are concentrated on the surface creating a bright color: red and reddish yellow which is the color of sulfur (in particular, its purple modification S_2 which forms during congealing of strongly heated vapors of sulfur), white spots -- are the snow from sulfur anhydride, and black spots are the volcanic ash. In the deepest layers, there can be compounds of sulfides of the magmatogenic origin type.

In spite of the fact that this is such a realistic model, one thing remains undisputed: among the objects of the solar system (at least those whose surfaces we have already successfully seen), Io appeared to be a record setter in volcanic activity which even fairly recently could hardly have been assumed. This is still the only (except, of course, for our Earth) example of a broadly developed modern volcanism and probably, continuing without eruption and exceeding in its intensity the volcanic activity on Earth.

We have talked about the capability for destruction of a few of the grandiose volcanoes on Mars and Venus. But on Io, which /142
is small in comparison with Earth planets (in its dimensions it is almost the same as the Moon) more than one hundred volcanic caldera have been discovered which are 200 and more kilometers in diameter, that is, ten-100 times exceeding those of Earth! Around many there are visible flows of erupted or congealed lava extending for several hundreds of kilometers and with a width of dozens of kilometers; this also many times exceeds ordinary Earth scale. In truth, the volcanoes

themselves are comparatively low, there are no great gradients of altitude on the surface of Io and no interplanetary ravines predominate. Only in the polar regions does one encounter individual mountains with altitude up to 10 km. On the whole, the relief is smooth and at the same time one does not detect any outcroppings of rock. All of this, it would seem, favors the hypothesis according to which Io has a very thin upper layer of hardened crust under which one finds melted sulfur.

Moreover, the individual hills with pronounced size and deep depressions encountered on the inter-volcano plains cannot be explained within the framework of such a model starting with conditions of isostatic leveling. Therefore, it is more likely we are talking about individual regions as melt, subsurface "sulfur seas," with temperature no lower than +110°C at which sulfur melts. The temperature itself of the surface in the region of the equator amounts to -140°C and in the polar regions it is 50° lower. Even in local sections associated with volcanic activity, one detects a temperature of 10°C, that is, 150° higher than the average surface temperature. With such a low temperature, the vapors of sulfur erupting on the surface very rapidly are cooled and this explains the formation of its red modification in the volcanic deposits besides the two most extensive allotropic modifications for Earth conditions of a lemon yellow and honey yellow coloration.

The presence of volcanic activity and the absence on the surface of impact craters larger than 1-2 km is evidence of the fact that the surface of Io is very young, its age obviously does not exceed one million years. Figure 47 shows a section of the surface close to the south pole in which separate fissures and ejecta are visible (in the upper right part and to the right of the terminator) and also several plain regions located at different levels with a more elevated part in the upper left corner. The /144
plain regions are separated from each other by escarpments, possibly formed in the process of cooling of the lava (including subsurface melts of sulfur) and subsequent erosion. These and also the polar regions with

Figure 47. A section of the surface of Io close to the South Pole. A broad valley is visible with steep slopes; inside it is a system of escarpment and fissures (photographed from Voyager 1).

tectonic cracks and grabens, obviously, are relatively old sections of the crust and to the least degree were modified by modern volcanism. Nevertheless, they contain indications of its determining role in the evolution of the surface on a global scale and at the same time are evidence of the weak degree of erosion which is additional confirmation of the limit of evaluations of age made earlier. /145

Other Galilean satellites are not as turbulent in geological activity as Io is. However, the surface of each of them is in itself phenomenal, possessing some unique property. The well-known largest reflective capability of Europa proved to be a heavenly body with an exceptionally smooth surface, the smoothest of those known in the solar system. Maximum variations of relief are evaluated not in kilometers but in dozens of meters, and this is on a global scale for a body whose diameter is only 350 km smaller than that of the Moon! It is at just this altitude (on the order of 50 m) that there are chains of small hills and foothills differentiated on the surface at the same time that separate details in the relief on the surface of Ganymede and Callisto are reached with at least ten times greater altitude. Craters are almost not visible on the surface of Europa, and in each case of craters larger than 5 km in diameter, it leads to a concept of a comparatively recent formation or periodically occurring processes of "renewal." One more phenomenon of this satellite was the presence of a large quantity of linear structures -- intersecting bands at different angles actually cutting across its surface and extending in different directions for hundreds and thousands of kilometers, sometimes encompassing half of the circumference (about 5,000 km). The width of these bands, on the average, is several dozens of kilometers, but the areas go up to 200-300 km and the depth usually does not exceed a few hundred meters (Figure 48).

Figure 48. A fragment of the surface of Europa with a system of cracks formed in the ice crust, probably as a result of tectonic processes. The length of the cracks is several thousand kilometers, and the width is more than 100 km. On the surface, there are no craters, which is evidence of its young age (photograph from Voyager 2).

What caused their formation? In order to understand this, first of all, we have to remember that from an analysis of the spectra of reflection of the Galilean satellites, a hypothesis was put forward about the presence on the surface of Europa and Ganymede of water ice. Measurements from spacecraft confirmed the accuracy of this proposal. Also, a surface temperature was determined which in the region of the terminator amounted to 93 K ($-180^{\circ}C$) and in all 30-40 K larger at midday. With such a temperature, the surface of course, is completely

frozen. An explanation of the surprising smoothness of Europa and the abundance of fiber-like bands can be found within a framework of models according to which a layer of ice extends for a fairly great depth. However, it would be convenient to have a situation which could be looked at in more detail discussing the layer of permanently frozen ground and rivers covered with ice on Mars; a solid ice crust, obviously lies only on the very surface, which covers a tremendously more extensive layer consisting of a mixture of comparatively loose /146
"spongy" ice from water. This mixture, called brash ice, is well known to us on Earth. It is formed before the beginning of the freezing over due to overcooling of the water in the mountain rivers and the rivers with rapids and also in the lower reaches of hydraulic units, choking up water collectors, filters, and preventing their normal operation.

Both layers -- the brash ice and the ice cover -- consist of an intrinsic upper shell on the Europa, whose maximum thickness is estimated at approximately 100 km. It is proposed that its partially melted state is due to a mechanism of regeneration of internal heat. Under the brash ice, possibly, are hidden significant variations in altitude on the surface, which is a solid silicate substance similar to that found in the Earth's oceans and which completely level the relief of the bottom. Only on Europa is the brash ice comparable to the crust itself and not to the hydrosphere.

The thread-like bands on the surface are not so different from the cracks in the upper solid layer of ice occurring under the effect of internal stresses created by expansion and contraction of the brash ice. With the formation of cracks, subsidence of the ice can occur, /147
its mixing, rising of the brash ice to the surface and its freezing. Thawing of the cracks with fresh, loose ice (and this means less solid) easily explains the occurrence of white bands on a background of the dirty surface of the ice and dark bands, possibly, are formed where instead of ice on the surface, there is a dark substance which is much deeper. These accompanying processes of mixing the large massifs of ice of a type of movement of glaciers (ice forms) must lead to wearing down the nonuniformity of the relief of the surface, in particular, lead to the disappearance of large craters of impact origin, which explains the fact of their absence. Obviously, the time scale of these processes comprises from units to several dozens of millions of years if one pays attention to the number of craters with small dimensions retained on separate sections of the surface.

The even older surface of Ganymede, the largest of the Galilean satellites, exceeds in its dimensions by almost 500 the dimensions of Mercury. This outer satellite is the one most similar to the Moon (see Figure 43) although with observation from close up, one observes very great differences. The most remarkable property of its surface was the presence of numerous branching "bundles" with long parallel furrows (troughs) and extensive crests concentrated in the light regions. Many dark areas are adjacent to them, scattered over with comparatively shallow craters whose diameters are from units to several dozens of kilometers. At the same time, light areas of the craters on the surface are considerably less (but more than, for example, on the lunar seas). A large dark area is particularly pronounced on the side of Ganymede opposite to Jupiter, extending for more than 3000 km. Probably, it is an example of a more ancient crust not covered with later deposits as occurred with the light regions. In certain dark areas, the residue of old, large basins can be made out. With the formation of one of the largest ancient basins, are related well differentiated diverging concentric rings occurring during impact.

Analogous ring-like structures were even more clearly visible in a few areas on Callisto. whose surface basically is like the surface /148
of Ganymede in the dark regions. Such regions can be looked at as a type of "window" into the earlier period of evolution of the Galilean satellites. It is because of this that the degree of their saturation by craters in the cross section of several dozens of kilometers is approximately similar to the degree of saturation observed on the ancient uplands of the Earth group of planets and the Moon. The formation of these uplands involve, as we have seen, the completed period of intense bombardments about 4 billion years ago. Of course, one must mention that this comparison is allowable in conditions which are approximately similar to these processes in internal and external regions of the solar system.

The morphology of the "bundles" of parallel furrows in the light regions of Ganymede is well differentiated on the photographic surface (Figure 49), particularly in the region adjacent to the terminator photographed with high resolution (Figure 50). The width of these "bundles" reaches several hundred and the length, several thousand, kilometers;individual furrows have a width from 5-15 km and depth of several hundred meters (the latter is determined according to the value of the shadow thrown at the terminator). In the fields of greatest concentration, they divide the entire surface into separate polygons with dimensions of a few hundreds of kilometers. The hypothesis is put forward that such landscapes impressed one as a period of the most geological activity of this satellite when the crust was particularly mobile and tectonic processes occurred which are reminiscent of the shifts and deformation of continental platforms on Earth. Then, folds were formed due to horizontal shifts with relative shift and perpendicular branching as is clearly visible, for example, in the upper part of Figure 49 and also individual ridges, "squeezed" from the cracks which occur in the crust. These formations are younger than the dark regions and again it is possible to judge them according to the number of craters whose density in these sectors of the surface is approximately a magnitude smaller. In age, probably they correspond to the sea region on the Moon.

Similar to Europa, the surface of Ganymede is covered with ice. Besides the comparatively high albedo and spectra of reflection in the near infrared region, the craters which form during impact of the meteorites give definite proof of the existence of surface ice. /150
Examples of these craters are visible on the photograph of a section

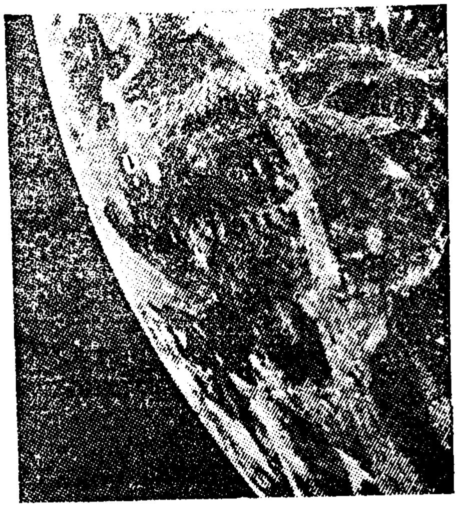

Figure 49. A fragment of the surface of Ganymede with a system of numerous troughs dividing the crater surface into individual sections extending from a few hundreds to one thousand km (Voyager 1 photograph).

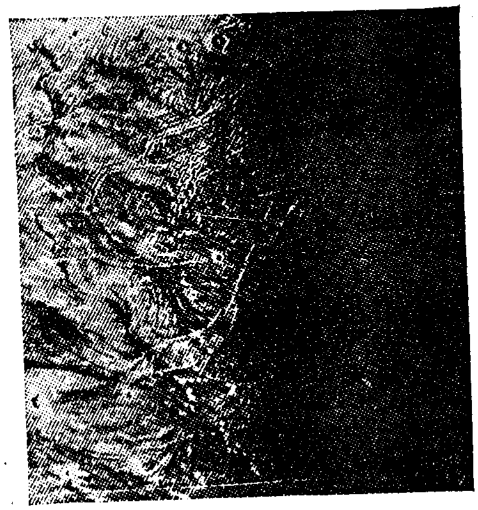

Figure 50. A large-scale image of troughs on the surface of Ganymede. These linear structures, obviously, were formed in its earliest history as a result of tectonic processes whose traces are retained on the ice crust (Voyager 1 photograph).

of the surface of Ganymede (Figure 51). In distinction from the lunar or martian, in them a concave bottom formed during rapid cooling of a current and no loose material is observed. A large crater in the upper part of the photograph has a diameter of about 150 km and a beamlike structure is visible, layers of ejected ice surround the crater, ejecta and outcropping of "fresh" ice along the rays. The absence of significant variations in altitude on the surface (more than 1 km) also are evidence in favor of concepts about the ice surface of this Jupiter satellite.

The oldest satellite in the family, having the greatest degree of /151 saturation of impact craters, not only among the Galilean satellites but in general among the heavenly bodies known to us is the satellite Callisto (see Figure 43). The density of craters is a number of regions of Callisto is as great as that on Ganymede in dimension and obviously have reached values close to the maximum which can be discussed according to a mosaic image of this disk compiled from nine photographs taken from Voyager 2 (Figure 52). The number of just the large craters reaches several hundred and around several of these one observes bright beams.

The two lightest sections on the generally dark surface of Callisto are tremendous basins of the lunar sea type with concentric rings which have been called "bulls eyes." The dimensions of the largest basin, shown in Figure 53, exceeds 600 km and the number of

Figure 51. A fragment of the surface of Ganymede with "stars" of ice around the craters of impact origin; the "stars" are evidence of the ice crust of the satellite (Voyager 1 photograph).

rings is at least 15, with a diameter of the most outer ring about 2600 km. These formations also are covered with craters; however, their density decreases toward the center of the basin.

The texture of the surface on the left edge of the photograph is formed by a tremendous number of craters which are actually adjacent to each other and in the direction toward the right edge, a significant part of the craters was broken down by a shift and stratification of the surface material with the formation of the basin. Moreover, then no noticeable deepening remained on the surface of the basin itself and also the swells and crests on its periphery are similar to those which were formed on the surface of the Moon, Mercury and Mars. Instead of these, concentric rings were retained which are traces of impact waves occurring during impact of a large meteorite.

Similar configurations were not retained on the heavenly bodies with a silicate crust. These circumstances clearly indicate that the surface of Callisto is covered with an easily melted substance rapidly filling the depressions and "freezing" the process of propagation of oscillations. On the whole, the surface of Callisto is fairly smooth and the depth of the craters is not great. All of this makes it possible to assume that the upper layer of Callisto, like Ganymede and Europa, also basically comprises ice. Weak signs of ice absorption in the spectra of Callisto, like the very low albedo of this satellite (even twice as large as on the Moon) can be explained by the fact that the surface is made up of "dirty" ice, possibly, with admixtures of silicate substances and this coating is also covered with a layer of /153
meteor dust. In the final analysis, the most primary cause obviously is the absence of active endogenic processes which would essentially keep the surface of Callisto in a "protogenic" form from the moment of completion of the significant stage of intense bombardment about 4 billion years ago except for basins formed later.

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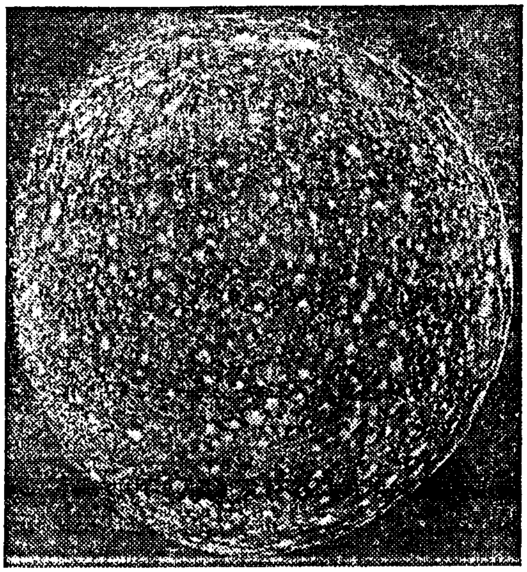

Figure 52. Maximum saturation by craters of the surface of Callisto. Many of the craters retain beam structures. The image is made up of a mosaic of photographs taken from Voyager 2.

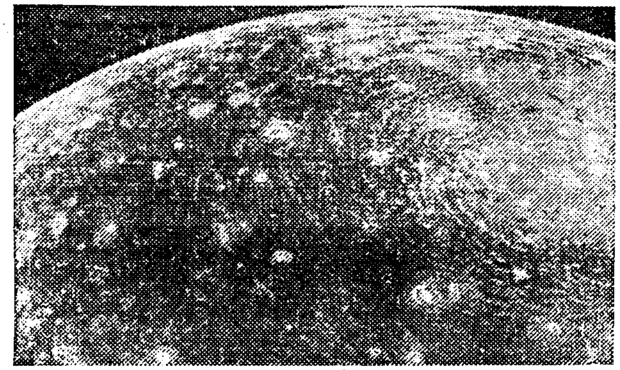

Figure 53. A fragment of the surface of Callisto with a resolution of about 7 km. On the right -- a basin (similar to that visible in Figure 52 in the upper right) with cross section 600 km with a system of concentric rings whose outer diameter reaches 2600 km. They were formed during impact of the meteorite simultaneously with the basin itself and have outcroppings of ice. This formation reminds one of a bulls eye and has been named Valhalla (photograph from the Voyager 1).

The closest brother of Callisto from this point of view is Amalthea. Discovered by the American astronomer E. Barnard in 1892, that is, almost three centuries after the discovery of the Galilean satellites of Jupiter, it looks like an asteroid with the largest and smallest dimensions 270X150 kilometers (see Figure 44) which is almost a magnitude larger than the dimensions of Phobos. However, in comparison with the Galilean satellites, this body is very small, although it has proved to be approximately twice as large as had been proposed from ground observations. This is explained by the fact that detection of Amalthea turning in orbit at an average distance of less than 200,000 km from the bright disk of Jupiter was an extremely difficult problem for the astronomers. Its surface is primarily red and partially black in color and as a whole is very dark (albedo from 4 to 6%), and it is strongly craterized. Neither in color nor in reflective capability is it similar to the surface of the Galilean satellites. With comparatively small dimensions, Amalthea has very large craters with a correct dish-shaped form. The largest crater called Pan (diameter 90 km, depth 8-10 km) and Geya (diameter 75 km, depth 10-20 km) obviously belonged to the largest dish-shaped craters in the solar system.

It is interesting that Amalthea to the greatest degree shows the effect of the powerful magnetosphere of Jupiter. This is apparent in that its surface is unexpectedly warmer than one would assume starting with calculations of the radiation balance. Such an additional source of its heat could be the energy-charged particles and emission of Joule heat. One could hardly doubt that like the satellites of Mars this body is a captured asteroid; it is much less probable that this is a relict of the stage of formation of the Jupiter system.

Surface of the Satellites of Saturn

Now let us become familiar in more detail with Saturn's satellites about which we have discovered quite a bit after the flights of the Voyager 1 and Voyager 2 spacecraft. These satellites form a large family (see Table 2 and Figure 54) whose individual members are in dynamic interrelationship with each other and with the rings of the planet. On the surfaces of comparatively large bodies with spherical shape, one gets the impression of traces of a number of geological processes. In turn, six of the newly discovered satellites make up a unique collection of small asteroid-like bodies of irregular shape with several different properties of the surface. /154 /155

All of the large satellites of Saturn except for Titan and Phoebe have, as has already been said, ice surfaces. Low average density is evidence of the fact that these bodies are almost completely water ice; among them are several with large relative content of rock on Mimas, Dione and Rhea. Nevertheless, although they are comparatively smaller than let us say on Ganymede or Callisto, on the surface of the majority of satellites of Saturn we find manifestations of their endogenic activity.

A montage of images transmitted by Voyager 1 gives us a concept of the relationship of the reflective properties of satellites found within the orbit of Titan (Figure 55). The brightest, not only in Saturn's family but possibly in the solar system in general is Enceladus. Its albedo is close to 1 (that of fresh fallen snow) and a number of its remarkable features are related to this. At the same time, Phoebe (not shown in Figure 55) has an albedo of a total 0.05, hardly distinguishable on the dark background of cosmic space.

Of all of the large satellites of Saturn, only Hyperion has an irregular shape (see Figure 62) in spite of its comparatively large dimensions (460X260X220 km) comparable to the dimensions of Entselad and Mimas. A hypothesis is being put forward that this is the remains of a more massive body broken down as a result of catastrophic impact with another. The reddish coloration of its surface in combination with a fairly narrow albedo does not exclude the presence of water ice, whose spectral characteristics were actually detected. It is possible that Hyperion as a whole consists of ice, but its surface is strongly contaminated with the dark material of the carbonaceous chondrite type, which it is assumed Phoebe is made up of.

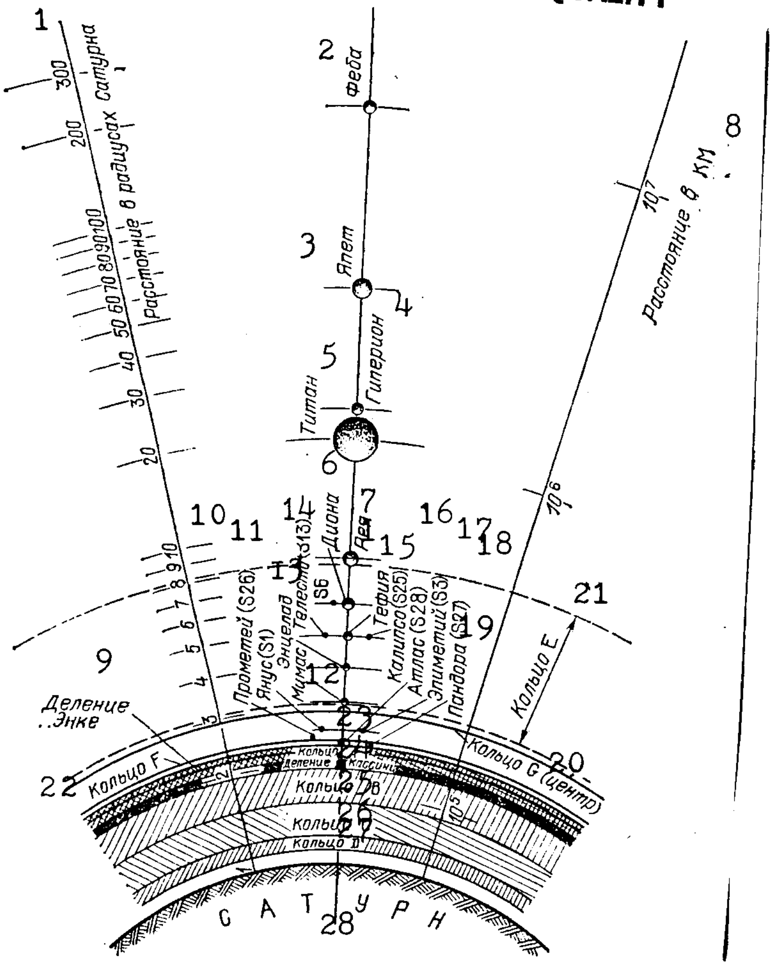

Figure 54. Diagram of the position of the rings and satellites of Saturn. The distances from the center of the planet are indicated in the radii of Saturn Rc and in kilometers. The letter S with numbers means the recently discovered satellites.

Key: 1. **distance in Saturn radii**; 2. Phoebe; 3. Iapetus; 4. Hyperion; 5. Titan; 6. Dione; 7. Rhea; 8. distance in km; 9. Enke division; 10. Prometheus (S26); 11. Janus (S1); 12. Mimas; 13. Enceladus; 14. Telesto (S13); 15. Tephiya; 16. Calypso (S25); 17. Atlas (S28); 18. Epimetheus (S3); 19. Pandora (S27); 20. ring G (center); 21. ring E; 22. ring F; 23. ring A; 24. Cassini division; 25. ring B; 26. ring C; 27. ring D; 28. Saturn.

The idea that Phoebe could be the source of a dark material for Hyperion and Iapetus was put forward in an attempt to explain primarily the strange asymmetry and reflective properties of Iapetus which we mentioned earlier. The ice surface of this satellite has its own dark detritus on the hemisphere turned toward movement in orbit, so that its albedo is decreased by a magnitude (Figure 56). It was proposed that the particles lost by Phoebe during bombardment of it by /156 meteorites had to have been a spiral gradually drifted inside the system of Saturn as a result of the Poynting-Robertson effect described above. In the process of this drift, they are incident in the zone of orbit of satellites neighboring Phoebe settling onto the anterior of their hemisphere.

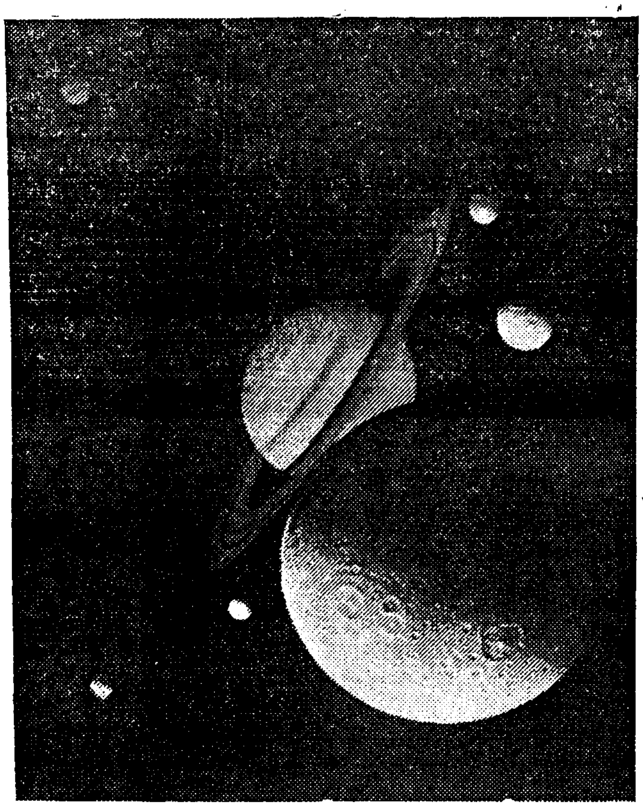

Figure 55. The Saturn system within the limits of orbit of Titan in the form of an artificially applied image of the planet and satellites. The images were transmitted during a flyby of the Voyager 1 in November 1980. In the front of the picture is Dione, on the right, Tephiya and Mimas, on the left, Enceladus and Rhea and on the upper left, Titan (a montage of photographs).

Such a model, however, does not satisfy the new observation data. In the first place, it has been discovered that spectral characteristics of the material surface of Phoebe and the dark coating on Iapetus have great differences, that is, their nature is not uniform. Secondly, it was found that the surface of Yapet on the light side is speckled with craters whose bottoms have a similar dark coating (see Figure 56). Therefore, as the most probably, we take the hypothesis of intrinsic internal source of thermal material on Iapetus as a result of geological activity which, in particular, involves methane eruption from its interior. However, this model does not given an explanation of the causes for primary evacuation of deep material only on one half of the satellite of Saturn. /157

First of all, there is no reliable information about the surface of Titan. A definition of the parameters of its atmosphere (which we will discuss in detail below) makes it possible, nevertheless, to apply more strict limitations to the chemical composition and combined state of matter which covers the surface. Within the framework of the atmospheric model shown in Figure 83, it is adequately realistic to present a concept of the cyclic methane exchange between the surface of the satellite and the /158
atmosphere. The value of temperature of the surface does not contradict the hypothesis about the existence on it of broad basins of liquid methane. Do they cover the surface as a whole or a large part of it like the water on Earth? What is their depth and what is under them? In what relation to methane do we find more complex products

and other (unlimited) hydrocarbons? And finally, how does this amazing world occur in our solar system, all of these questions we hope to answer with a future study of Titan.

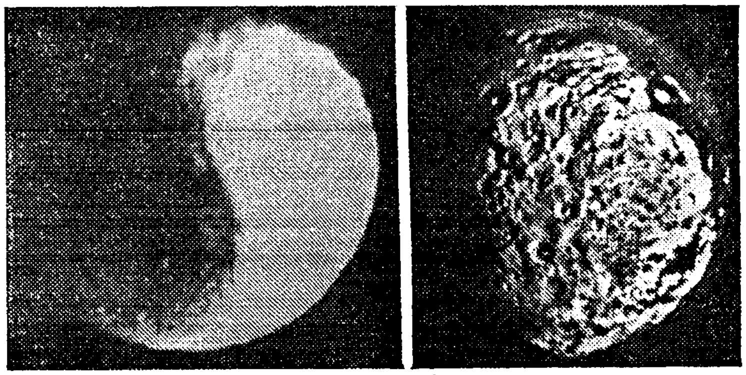

Figure 56. The satellite of Saturn, Iapetus. On the left, a Voyager I photograph, on the right, Voyager 2 photograph obtained with high resolution. On both photographs, tremendous differences are clearly visible in the reflecting properties of the anterior (in the direction of movement in orbit) and posterior hemispheres. Both hemispheres are strongly craterized.

The five large satellites within the orbit of Titan have much in common, but they also have their own specific characteristics. Rhea, in its dimensions, is close to Iapetus (cross section approximately 1500 km) where at the same time Tephiya and Diona have diameters of about 1,000 km and Mimas and Enceladus -- a total of 400-500 km. Moreover, on Rhea, for example, there are fewer signs of geological activity than on some of its less massive companions. The surfaces of all the satellites with the exception of individual regions are strongly speckled with craters from the smallest to 50 km or larger. But the density of the number of craters and the distribution of large and small craters even in the old sections of the surface is not uniform. This has led to a hypothesis that bombardment of bodies in the Saturn system occurred in two basic stages separated in time: the first, very ancient, relating to the period of formation of the planet and its satellite; the second, a much later one, involving either a breakdown in one of the early significant satellites and incidents of its fragments on another body, or with an intense period of comet activity in the region of the Saturn orbit.

Figure 57 shows the hemispheres of Rhea turned toward the side opposite the direction of movement in orbit. It is darker than the opposite and on it light bands are more noticeable. An even more complex system of bands is observed on the dark (also, the reverse direction of movement) hemisphere of Diona. Obviously, this is an outcropping of fresh ice occurring at a comparatively early stage of internal activity of satellites and not masked by subsequent deposits. One of the possible scenarios for the formation of these configurations involves the primary formation of troughs or cracks along which, later on, in the process degasification of the interior, /160

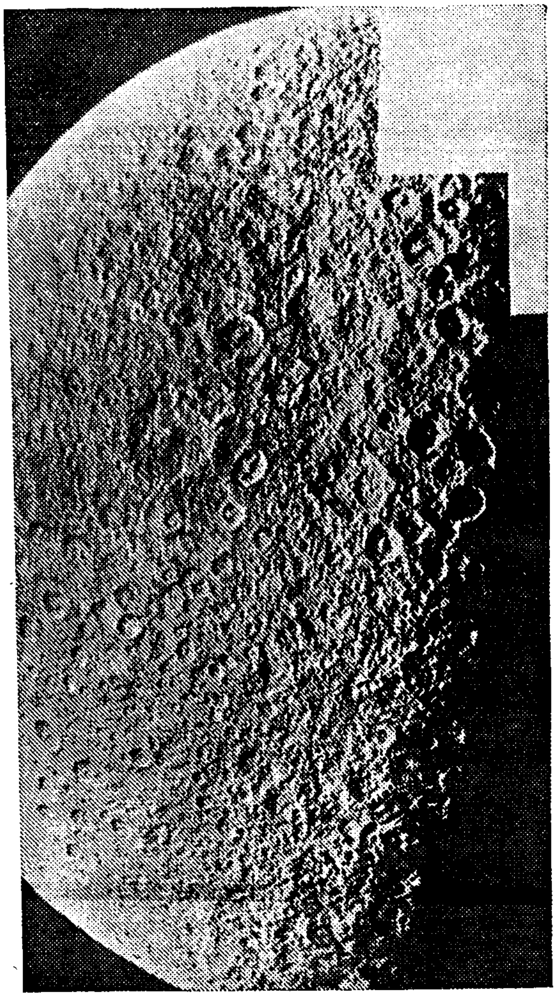

Figure 57. An image of Rhea obtained from the Voyager 1. The distance to the satellite was 1.7 million km, resolution of details on the surface 30 km.

on the surface, water poured out (possibly along with methane). The long troughs which are not filled with fresh ice are encountered only on the craterized surface of the lighted hemisphere of Diona as is clearly visible in Figure 58. A tremendous trough or more accurately fault which has been named the Itaka fault extended for almost three /161 fourths of the perimeter of Tephiya which is the neighbor of Diona (Figure 59). Its width is about 100 km and its depth reaches several kilometers. On the whole, the surface of Tephiya is more ancient inasmuch as it is more strongly saturated with craters. A cross section of the largest crater Odyssey has been significantly obliterated since its formation; it reaches the dimensions of Mimas!

Mimas, in its density of craterization can be compared with Tephiya, although the craters on its surface to a large degree are masked by deposits of comparatively small material (Figure 60). This fact can be explained if one takes into consideration that the acceleration of the force of gravity on Mimas is a total of 6.4 cm/s^2; therefore, the fragments which formed during collision of meteorites with it can easily have left its field of gravity /162 distributed along the orbit. In the future, they probably gradually settle to the surface, covering it more uniformly than in the case of local ejecta on the more massive bodies.

The very impressive formation on Mimas, of course, is the Artur crater with diameter 130 km which equals one third of the dimensions of the satellite itself. Its depth is almost 10 km, the height of the central hill is 6 km and the ridge of the swell occurring during impact goes beyond the contour of the spherical shape of the satellite. This is explained by the fact that obviously, the crater was formed in a period when Mimas had lost its primary plasticity. Therefore, the force of gravity was not retained, so that in

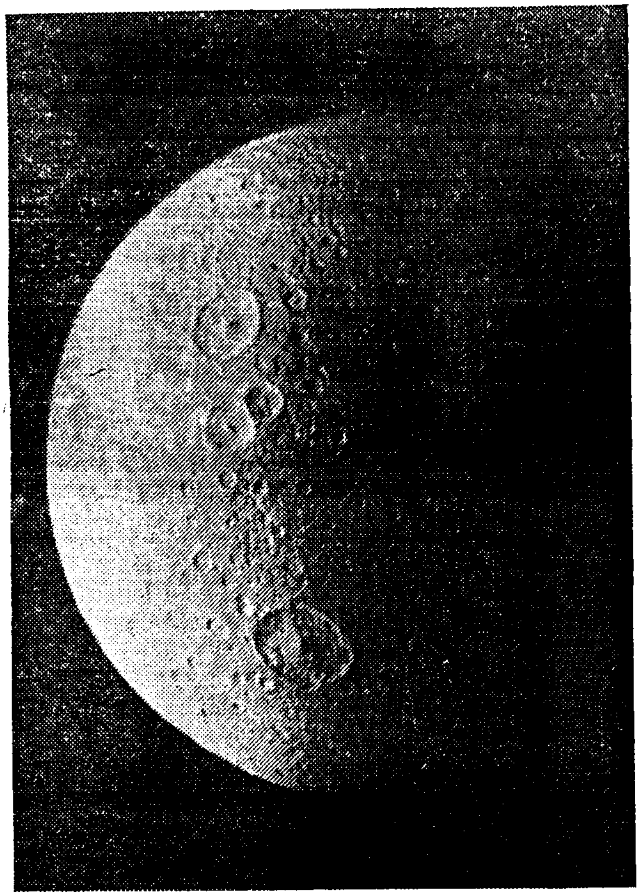

Figure 58. Dione, fourth in dimension of Saturn's satellites. A mosaic of images transmitted by Voyager 1 from a distance of 162,000 km. The dimensions of the largest crater on the surface is about 100 km. Below -- a winding trough, probably formed as a result of a fault in the ice crust caused by ancient active processes in the interior.

distinction from the Odyssey crater on Tephiya, the outline of the Artur crater is smoother without creating any deviation satellite from a spherical shape. Probably, the meteorite which formed this crater in its dimensions (about 10 km) was maximum; Mimas was broken into sections from impact with the larger body. Possibly the troughs or cracks on the surface extending for hundreds of kilometers and with approximately dozens of kilometers and depth up to two kilometers are related to this almost catastrophic event in its /163 life. For example, an alternative reason could be the ancient processes of internal activity on this satellite which is small in dimension.

Relying on completely well-founded concepts of the relationship of intensity of geological processes to the dimensions of the heavenly body, it would naturally seem that one could propose that the two twins -- Mimas and Enceladus -- differ little from each other. Moreover, Entselad unexpectedly appeared much more active and moreover the most active member of the Saturn family whose broad areas differ in their young surface with brightly pronounced traces of tectonic processes. From this point of view, Entselad can be considered an analog for Io in the Jovian family. There are no ancient large craters even on the craterized sections on Enceladus and on a significant part of the surface, they are completely absent (Figure 61). The age of these latter, obviously, does not exceed a few dozens of millions of years, that is, they are completely suppressed on a geological scale of time. Undoubtedly, these regions to a larger degree than the remaining, have undergone processes of deformation of the crust which probably were caused by movement in the stratified or even partially liquid mantle.

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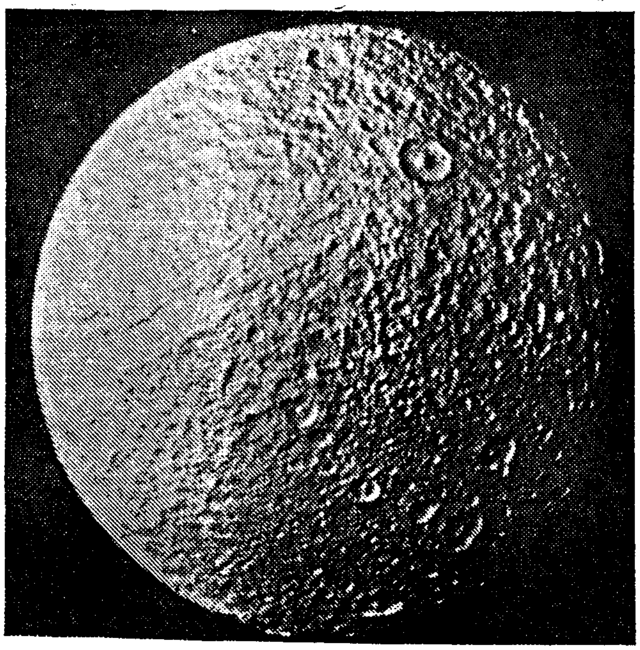


Figure 59. Strongly craterized surface of Tephiya. The image transmitted by Voyager 2 from a distance of 93,000 km. Maximum resolution on the photograph 5 km. Part of the surface below to the right is less saturated with craters which obviously involves the activity of the interior in the early history of the satellite. As a result of these processes, there is a system of tremendous ravines (troughs) extending for almost three fourths of the perimeter (top and left of center).

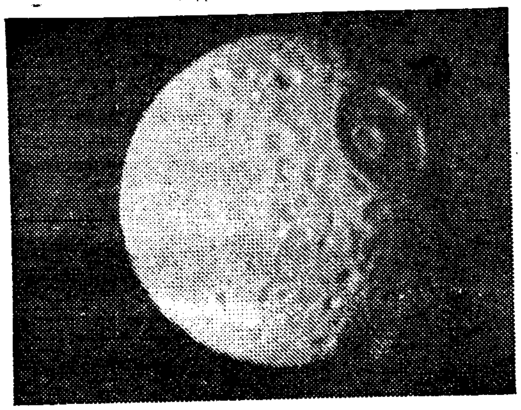


Figure 60. The first of the comparatively large satellites of Saturn is Mimas. The image transmitted from Voyager 1 from a distance of 425,000 km with details on the surface visible with a resolution of 8 km. The multiple impact craters are evidence of the ancient origin of the relief. The diameter of the largest crater is greater than 100 km and its swell protrudes over the spherical outline of Mimas.

It is impossible to exclude the fact that on the satellite even very recently inherent volcanoes were active or are continuing to be active -- with eruption of liquid water from the interior. And although such active volcanoes have not been detected during flights of the Voyagers, numerous ridges and igneous troughs in sections devoid of craters attest to the probable excesses of large masses of water on the surface.

Finally, it is impossible not to say a few words about the newly discovered small satellites of Saturn. Their special feature not only in the properties of the surface as much as in dynamic features of orbit are graphically illustrating a number of the celestial-mechanical principles (see Figure 54). From the five satellites closest to the planet with average diameter approximately from 50 to 200 km, the three first ones are called "shepherds," and the two others -- co-orbitals. These names are not taken by chance. This means that one of the satellites (Atlas) is in direct proximity to the exterior edge of ring A on Saturn and the two others (Pandora and

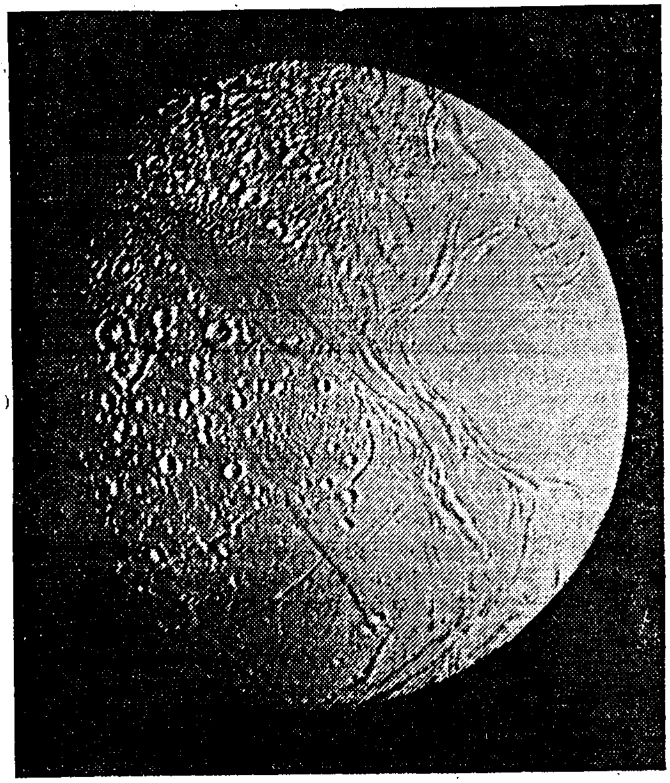


Figure 61. The Saturn satellite Entselad. A cross section of the largest craters on the left does not exceed 35 km. A significant part of the surface (right hemisphere) has on it traces of active tectonic processes (ridges, faults) which are evidence of the possible continuing activity of the interior. The absence of craters on these sections attests to the youth of the crust of the satellite whose age does not exceed 100 million years. Resolution on the satellite is about 2 km. (Photograph from the Voyager 2).

Prometheus) on both sides of ring F having a significant gravitational effect on distribution of particles and, correspondingly, the configuration of these rings. The co-orbital satellites (Epimetheus and Janus) are named thusly because they are found practically in identical orbits. Periodically (once every four years) they approach and due to gravitational interaction "exchange" their orbits. This "waltzing pair" has no analog in the solar system. Three more small satellites each of which has dimensions less than 40 km are called Lagrangian. We have already encountered the concept of the Lagrange points (see Figure 3). The satellites Telesto and Calypso are found at points L_4 and L_5 in the orbit of Tephiya and the satellite 1980 S6 -- at point L_4 in the orbit of Iona. /164 /166

All of the small satellites, like Hyperion, have an irregular shape with clearly pronounced traces of cratering on their surfaces (Figure 62). Obviously, in their composition, they are basically ice and are fragments of larger bodies broken down during collision at early stages of formation of the Saturn system. Part of them, probably, are genetically related to smaller fragments from which the rings of Saturn were formed.

The Rings of the Planet

A characteristic relict of the stage of formation in the family of satellites are rings of the planet which are detected at the present time in all of the planet-giants except Neptune. However, the discovery of the famous rings of Saturn by G. Galileo in 1610 and the Jupiter and Uranus rings even in our days has isolated a period of more than 350 years. One should remember that Galileo thought that he

was looking at the satellites of the planet and only the famous Dutch physicist H. Gugens (who discovered in 1655 the largest satellite of Saturn, Titan) described them 50 years later as rings. Another 200 years has passed since, as a result of theoretical studies, an outstanding scientist of the nineteenth century, English physicist J. Maxwell discovered that these are not solid bodies nor liquid formations around the planet but a set of individual small bodies or particles. In other words, they were broken up by gravitational perturbations inasmuch as the solid formation contradicts the condition of stability of the rings at a relatively small distance from the planet. This conclusion was soon experimentally confirmed by a famous Russian astronomer A. A. Belopol'skiy who was the first to indicate the differential rotation of the rings and also independently made observations at the American and French observatories. It was established that the inner part of the system of rings has a higher rate of rotation than do the inner, which corresponds to the required difference in values of the first cosmic (circular) velocity which is /167
inversely proportional $R^{1/2}$, where R is the distance of the satellite from the planet.

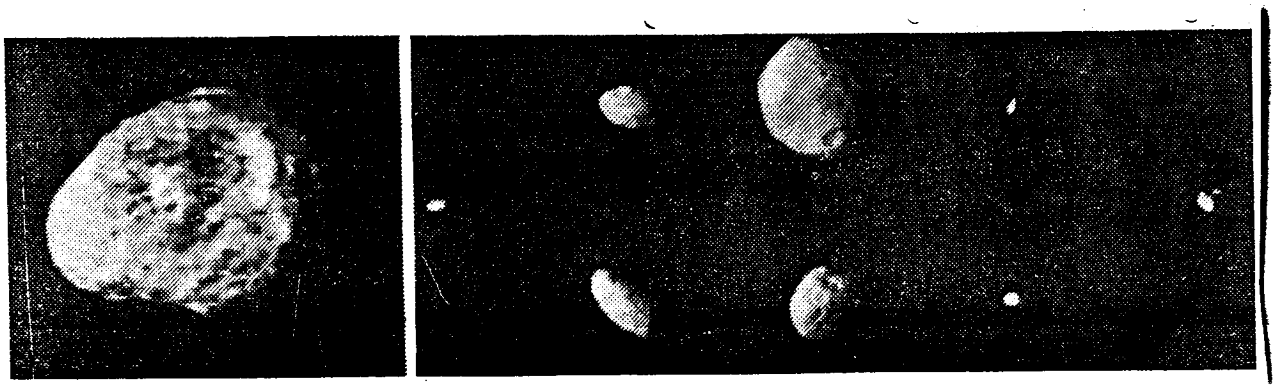


Figure 62. Small Saturn satellites (Voyager 1 and Voyager 2 photographs). On the left -- Hyperion, behind it, Atlas (the "shepherd" of ring A), Prometheus and Pandora (the "shepherds" of ring F), the co-orbital satellites Epimetheus and Janus, two Lagrangian satellites of Tephiya (Calypso and Telesto) and the Lagrange satellite, Dione (1980 S6).

The ring of Jupiter was discovered in 1979 with the flyby of the Voyagers (Figure 63). In truth, the hypothesis about its existence had been predicted in 1960 by the Soviet astronomer S. K. Vsekhsvyatskiy, and in 1976 such a possibility was more definitely indicated by the American physicist M. Ekun and N. Ness, who analyzed the character of distribution close to Jupiter of charged /168
particles which had been measured by the Pioneer 11 spacecraft. Like all of its satellites, the Jupiter ring is located in an equatorial plain at a distance of 55,000 km from the visible upper boundary of clouds which comprise about 3/4 of the radius of the planet and are approximately twice as small as the distance to Amalthea. The width of the ring is 6,000 km and the thickness about 1 km. It is formed of very dark particles and therefore its brilliance is eleven stellar values (that is, more than 10,000 times) weaker in comparison, for

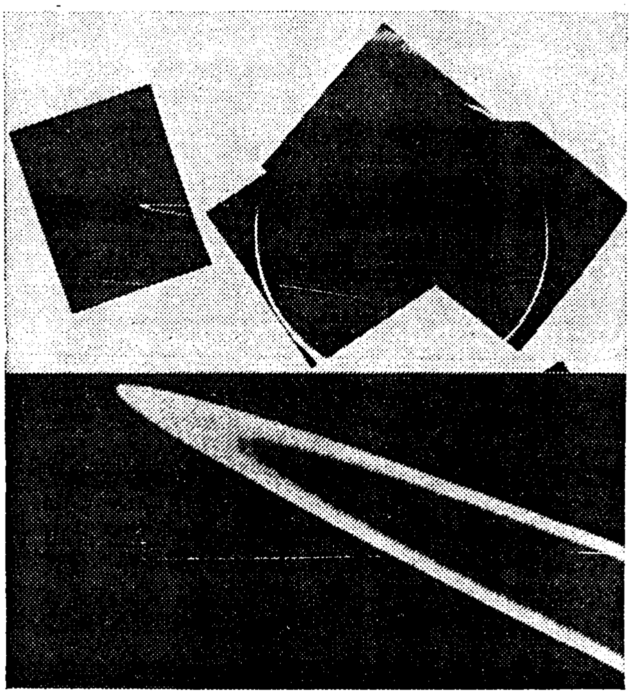


Figure 63. The image of the ring of Jupiter obtained from the Voyager 2. On top, the light limb of Jupiter with the ring. Below, a ring in a large scale. The width of the ring is 6,000 km, thickness about 1 km, its distance at the outer edge from the upper boundary of the Jovian clouds, 55,000 km.

example, with the rings of Saturn. Naturally, it is extremely difficult to observe from Earth and only soon after its discovery was it successfully identified by astronomers at the Mauna Kea Observatory who used a telescope with a mirror diameter 224 cm and sensitive receiver for emission in the near infrared field of the spectrum (for wavelength 2.2 μm).

The nature of the particles of the ring is unknown; however, one can assume that in its composition they do not strongly differ from the matter making up Amalthea. The dimensions of the particles are evaluated in limits of a few micrometers up to several meters. The presence of small particles definitely indicates, in particular, the great brightness of the ring during observation from the antisolar side, from cones of shadow -- once again with this positioning with the Sun obscured by Jupiter, images shown in Figure 63 were obtained. This means that with illumination of the fine particles (≈10 μm), the maximum brightness is created in the direction opposite the direction to the source (we are talking about the fact that the indicatrix of scattering is strongly elongated forward). This explains the clear separation of the rings on the dark background of space.

Obviously, the ring is an unformed satellite at the nearest distance from Jupiter found inside the so-called Rosh limit A = 2.4R is the critical distance from the planet with radius R within whose limits, as a result of the disruptive effect of tidal forces, the existence of the satellite is theoretically impossible. If such a satellite had been formed, then in its dimensions it would be approximately twice as large as Amalthea as estimates of the total content of particles in the ring have indicated. The Rosh limit was established for liquid satellites and therefore such a limitation does not contradict the discovery of the fourteenth satellite of Jupiter with cross section 30-40 km which is an asteroid-like body whose orbit /169
lies at the outer limit of the ring, that is, at a distance of 1.8 R_J. As was indicated in the 1940's, the well-known English astronomer and geophysicist G. Jeffries believed that the internal stresses necessary

for a breakdown of a solid satellite can occur only with fairly large dimensions of it. For example, the strong approach to Jupiter of a body with diameter more than 500 km proved to be catastrophic.

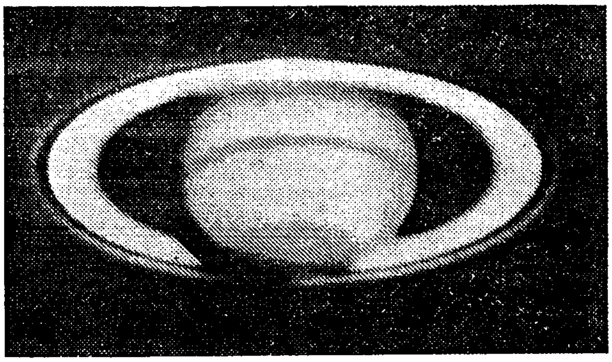


Figure 64. Photographs of Saturn from Earth obtained at the Catalina Observatory at the University of Arizona.

In distinction from the ring of Jupiter, the famous Saturn rings have been well observed from Earth thanks to the fact that the particles which formed them have a high albedo in the visible range of the spectrum and the rings themselves are considerably more extended. The angle between the plane of the ring and the direction to Earth changes within limits from 0^{o} to 28^{o} and the Earth observer therefore sees them at different angles (we are talking about the difference in "openings" in the rings). At the same time, the brilliance of Saturn changes. Three basic rings are isolated (Figure 64): A (outer), B (middle) and C (inner). Among these, the brightest is ring B and ring C is very weak and difficult to observe; due to the low brightness of it, sometimes it is called crepe. Later, a report was made of the existence of two more very weak rings: one inside ring C and the other outside ring A which the International Astronomical Union named, respectively, D and E. Ring D was not, however, at first detected during the flyby of the Pioneer 11 past Saturn (for the limit of density corresponding to optical thickness 0.003), but these same measurements were confirmed by the presence of increased density of particles beyond the limits of ring A; the zone closest to it is /170
called ring F.

What did we know about the rings of Saturn before the flights of the Voyager 1 and Voyager 2 which gave us more complete information about its interesting natural formation?

All of the rings limited by ring F are found inside the Rosh limit and the most outer boundary lies at a distance of about 2.3 R_S. The width of the rings A and C correspond to about 17,000 km and ring B is about 28,000 km, but the thickness of them does not exceed 1-2 km (measurements of the Pioneer 11 gave a value with thickness less than 1.3 km). Between the rings, there are spaces, the most important of which is a width of about 5,000 km; between A and B are the Cassini divisions, and in between B and C the division is not precise. Sometimes, also a broad zone of decreased brightness is isolated in the middle of ring A as the Enke division. The existence of the divisions was explained by resonance perturbations in the orbit of particles by the Saturn satellites which was first drawn to our attention in 1884 by Kirkwood for whom we have named them and the minimums in concentric distribution of density of asteroids in the asteroid band (the Kirkwood doors). The mechanism in this case and in other cases is approximately similar. In the case of the Saturn rings, it was discovered that the period of rotation of particles inside each of the divisions is in a strict ratio (ratio 1/2, 1/3, etc.) with the sidereal period of one of several satellites of the planet. A theoretical analysis drew the conclusion that the determining role here is played by orbital resonance with the closest of the large Saturn satellites, Mimas and also with Enceladus and Tephiya.

According to the result of ground spectrophotometry, in the nearest infrared field of the spectrum, fairly convincing proof was obtained of the fact that particles of rings basically consist of ice made up of water and not ammonia (as was earlier proposed). This is particularly pronounced in the results of identification with laboratory spectra of the data of measurement on wavelength 2.25 μm. Studies in variation and brightness depending on the phase angle drew conclusions on the presence both of very small dust particles and particles with effective dimensions from one to dozens of centimeters. In optical properties, these particles differ from the particles of the Jovian ring, scattering the light incident on them primarily backwards or, as they say, in the posterior hemisphere. In turn, the results of radar measurements were interpreted, starting with a model /171 of the largest particles having dimensions up to 10 or more meters.

Studies from on board the Pioneer 11 essentially confirmed the presence of all of these populations. It was noted that the brightest ring B is a single layer of chunks with dimension on the order of 15 meters which were "immersed" into a thicker layer of particles with dimensions about 10 cm. At this time, in the scattering of light, the most effective fraction was significantly larger than small particles, obviously, formed as a result of collision and crushing with large blocks. These processes must compensate for sweeping out the dust as a result of radiation slowdown caused by the Poynting-Robertson effect. The ratio of populations and their density in the rings is different and this explains the large differences in optical thickness.

The high-quality images of the rings transmitted by the Voyagers (Figure 65, 66) and supplemented by other measurements significantly clarified many questions of the general morphology of the inner structure and nature of the rings, having presented this system as an extremely dynamic formation which explains a number of its interesting features.

First of all, spatial positioning of all the rings was made more precise (see Figure 54) including the weak ring D, which is closest to the planet, found a total of 7,000 km from the boundary of the cloud layer. Beyond the very narrow ring F, there is one more very weak ring G and outside it, ring E, whose optical thickness exceeds a total of 10^{-5} -- 10^{-6}. Ring E occupies a tremendous zone from three to eight radii of Saturn R_S. The orbit of Enceladus passes through the center of this zone. Obviously, the ring and the satellite somehow

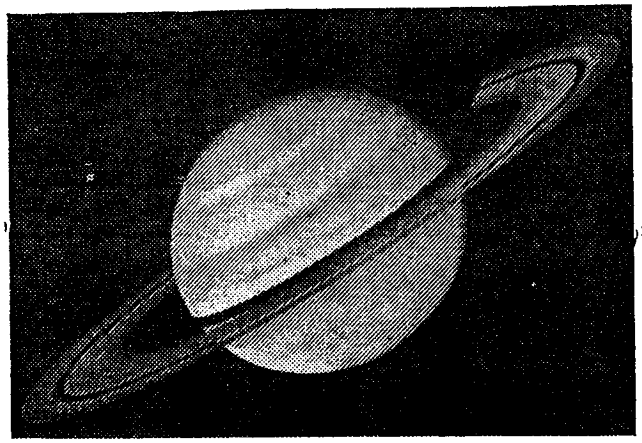


Figure 65. Saturn from a distance of 18 million km (resolution of details on the photograph about 350 km). This mosaic of images was transmitted by Voyager 1 and shows a weak-contrast striped structure of cloudy atmosphere and general morphology of the main rings C, B and A (in the direction from Saturn). A shadow from the ring on the disk of the planet is visible with a width of 10,000 km. The two points to the left of the bottom are satellites Tephiya and (close to the planet) Enceladus.

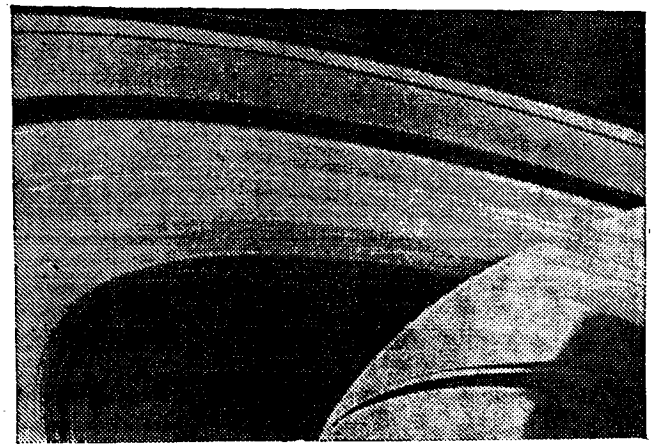


Figure 66. Large-scale structure of the rings with artificially increased contrast after treatment on the computer. The images transmitted by Voyager 1 from a distance of 1.5 million km. Through the ring, one can see the bright limb of Saturn. Numerous separate small rings are visible as well as the Maxwell, Gugens, Cassini, Enke, Kieler divisions (see Figure 68) and the narrow ring F.

are connected to each other; this does not exclude the fact that the origin of particles of ring E is caused by volcanic eruptions on Enceladus. The rings themselves E and G are fairly uniform and inside them one observes certain details. In distinction from them, the basic rings A, B, and C have an extremely complex inner structure.

It seemed that each of the basic rings consists of thousands (and possibly tens of thousands) of separate narrow small rings formed by /173
particles moving in their own orbit (see Figure 66, 67). Some of these orbits differ noticeably from the circular. This is explained by the fact that the resonance phenomena are stronger than was proposed, due to interaction of particles, not only with Saturn's large but also with the small satellites found close to the rings. The width of the small rings does not exceed a few dozen kilometers and more often, single kilometers. Among them, however, also one finds particles which are simply significantly smaller. All of this complex configuration can be explained assuming the periodic effects of tidal perturbations on the material of the rings. As a result, waves of density occur which propagate in a spiral in a radial direction. In other words, the rings are a dynamic system which is

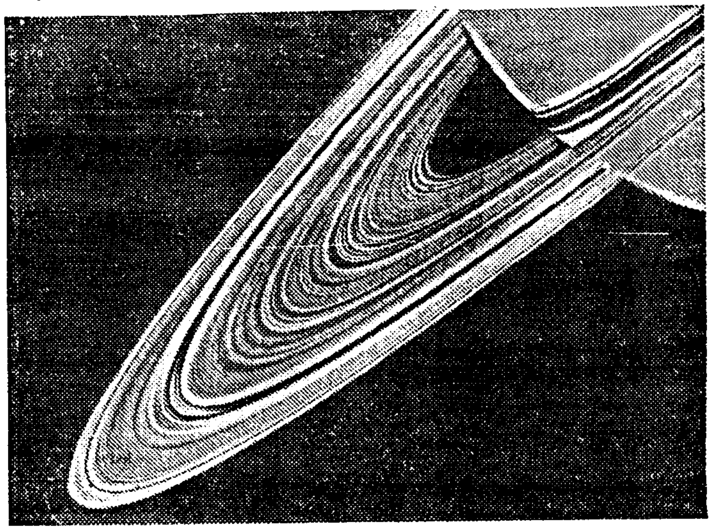
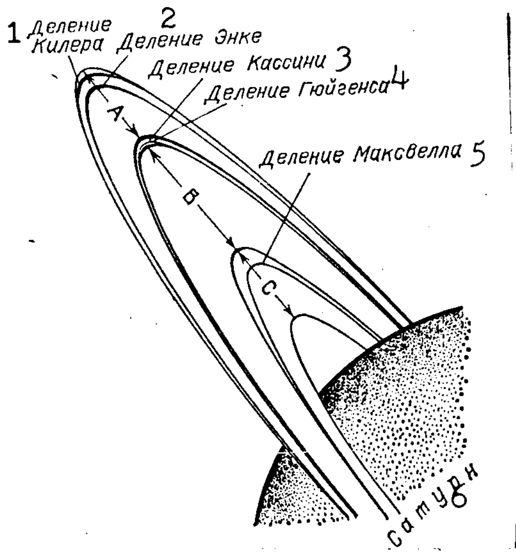


Figure 67. A mosaic image of Saturn's rings, showing a large number (at least 100) of the individual small rings. This complex dynamic structure, obviously, is the result of resonances caused by gravitation interaction of rings with a non-equilibrium shape of the planet and its multiple satellites. On the left at the bottom, ring F is visible (with widths less than 200 km), along with which is one of the satellite-shepherds of Prometheus (photographs from Voyager 1 at a distance of 5 million km).

found in resonance which, in appearance, can be similar to the grooves on a gramophone record. The excitation of energy which maintains a state of resonance, occurs, probably, both due to satellites and due to the shape of Saturn itself (its certain deviation from the uniform) which can be related to dynamic processes in its interior. For example, the drift of helium in the depths and its phase changes during interaction with metal hydrogen are related to this process by the American scientist R. Smolukhovskiy.

The effect of the shape of the planet a number of scientists have explained as the presence of several ring formations inside the Cassini division, closest to which is the outer edge of ring B which seemed, nevertheless, to be in the strict resonance mentioned 2:1 with Mimas and its elliptical shape sharply "tracks" the movement of the satellite in orbit. The satellites are connected to the presence of resonance in the general dynamic system of the planet by a number of other characteristic intervals in the rings which recently were named the Maxwell, Gugens and Kieler divisions. The position of the Enke division was made more precise (Figure 68). Inside these divisions also many separate small rings were apparent, but the total density of particles here is considerably smaller. A well supplemented concept of a fine structure of rings including the area of divisions was given by the experiment carried out on the Voyager 2 for discovering rings on Γ stars of Scorpius. For this purpose, using the onboard photopolarimeter, the change in intensity of light from the stars was measured according to which one could discover the rings in the process of flyby of the spacecraft (Figure 69).



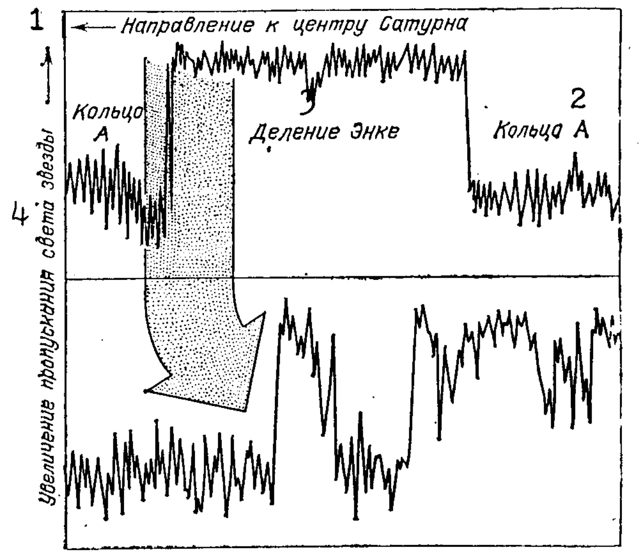


Figure 68. New nomenclature of divisions and rings approved by the International Astronomical Union.
Key: 1. Kieler division; 2. Enke division; 3. Cassini division; 4. Gugens division; 5. Maxwell division; 6. Saturn.

Figure 69. Variations in intensity of light of the Γ of Scorpius during its discovery indicated by the section of rings of Saturn on the drawing. Below -- a fragment of this section with high resolution indicating the fine structure of the ring in which narrow small rings had already been detected. The experiment was carried out on the Voyager 2 flyby in August 1981.
Key: 1. direction to the center of Saturn; 2. ring A; 3. Enke division; 4. increase in transmission of light by the star.

In turn, one of the satellite shepherds, Atlas, probably is responsible for the sharp inner boundary of ring A close to which it is found and Pandora and Prometheus cause the narrowness in ring F and a number of interesting features in its shape (Figure 70). Its width is no more than 200 kilometers and it consists of separate "strands" deflected from the elliptical trajectory and even sometimes intertwined one with the other. Along the orbit sometimes local clusters (accumulations) of particles are formed. The occurrence of these features is still not completely understood, but one or another primary mechanism is being used for the exchange of gravitational energy between particles of the rims and the satellite-shepherds on which other effects can accumulate. /176

The divisions are filled primarily with small particles. They are apparent in intensity of scattering of light forward so that when observing the rings not from the side illuminated by the Sun (as the astronomers are used to) but from the opposite side, "from behind Saturn," the Cassini division, for example, appears to be very bright. Similarly to it, the form of the rings themselves changes strongly:

thus, the brightest during observation from Earth, ring B, due to its high optical density, becomes dark and ring C, on the other hand, greatly increases its brilliance like separate parts of ring A. This character of scattering as a whole confirms the conclusions relative to the dimensions of particles obtained according to data of the Pioneer 11: there are numerous populations with dimensions from a few micrometers to dozens or more meters. The largest quantity of large blocks, probably, is found in ring B. /177

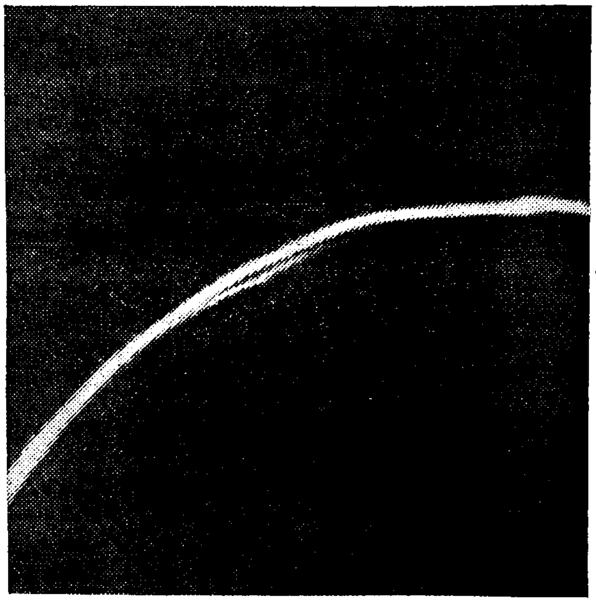


Figure 70. A fragment of ring F with its complex inner structure; separate strands are visible, slanted from elliptical orbit and thicknesses, probably, representing local accumulations of matter. The photograph is taken from the Voyager 1 from a distance of 750,000 km.

Certain additional information on the dimensions of particles can be obtained from an analysis of data on the pronounced color differences in the structure of rings which were detected by the Voyagers. For instance, ring C in the Cassini division can have a bluish shade at the same time that ring B has a reddish yellow shade. These differences, besides the effect of different optical thickness of the rings, can, however, more significantly depend on changes in chemical composition. Although as a whole, the conclusion is confirmed that particles of the rings are practically entirely made up of water ice, it is impossible to exclude the presence of admixtures unevenly distributed in different zones. It is interesting to note that if the color differences found of separate small rings do not change, this must mean that an exchange of material between them does not occur and the structure of the rings observed, obviously, is retained unchanged for hundreds of millions and billions of years.

Finally, it is impossible not to mention one more curious feature observed primarily in ring B. We are talking about the radial formations which show dark in the reflected and on the other hand light in the transmitted light over the backgrounds surrounding them (Figure 71). As to the existence of these formations which had been called "spokes," they were mentioned even in the past century by

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OF POOR QUALITY

astronomers; however, the results of these observations have been inconclusive and have not contributed to the accepted concepts. The length of the "spoke" reaches 10,000 km and the width, 1000 km. Their lifetime usually does not exceed a few hours, after which they "are smeared" along the ring and rapidly disappear and others occur anew. Probably, they are formed by clouds which are very small, particles with dimensions smaller than a micron line over the basic rings at an altitude of a few dozen meters. The nature of these formations, in all visibility, relate to the dynamic and electrostatic effects within the rings; however, no strict explanation has been found. The fact that for a certain time the "spokes" rotate more rapidly than the ring indicates their electrostatic nature; they have a period approximately coincident with the period of rotation of the planet (and this means its magnetic field). But even more, the gravitational forces begin to predominate and as a result the differences in velocity of movement of the particles along the radius of the ring leads to a breakdown in the "spoke." /178

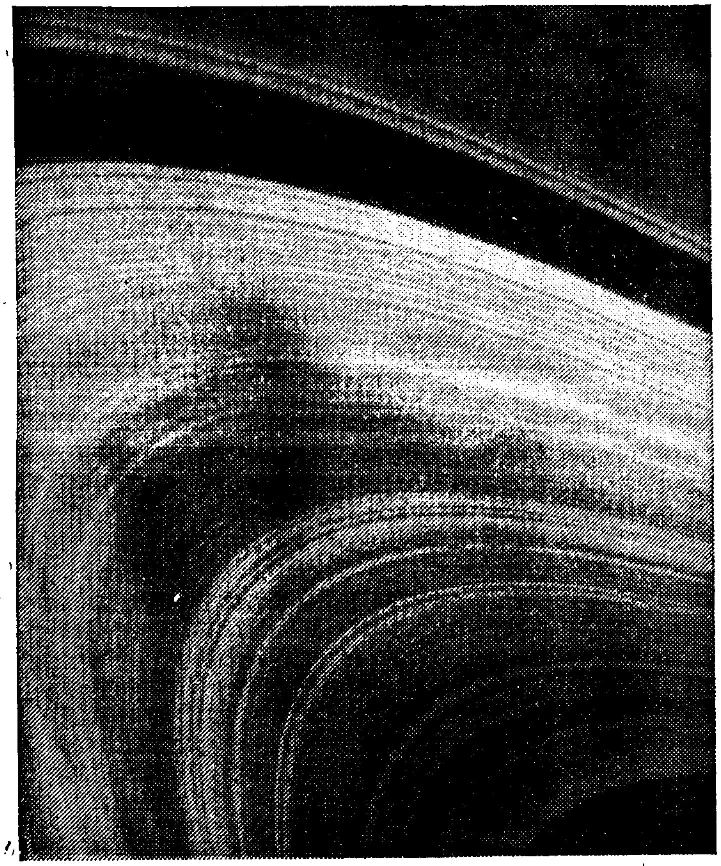

Figure 71a. Radial formations (spokes) in ring B. During observations from the site illuminated by the Sun, they appear dark.

Thus, we have confirmed how broad is the complex of problems occurring in relation to new data about the rings of Saturn. This is one more "call of nature" for physicists and theoreticians who wish to "apply" all of these facts in a single well structured system.

The greatest event was the discovery in 1977 of a change in the brilliance of a weak star covered by Uranus and the presence of rings /180 on this planet. Similarly to the ring of Jupiter, the reflective capability of the rings of Uranus is very weak (albedo less than 5%) and therefore in order to observe them, one needs improved astronomical instruments and high skill. At first, five rings were isolated which were designated as α, β, λ, δ and ε in the direction going from the center of the planet so that ring ε is the farthest

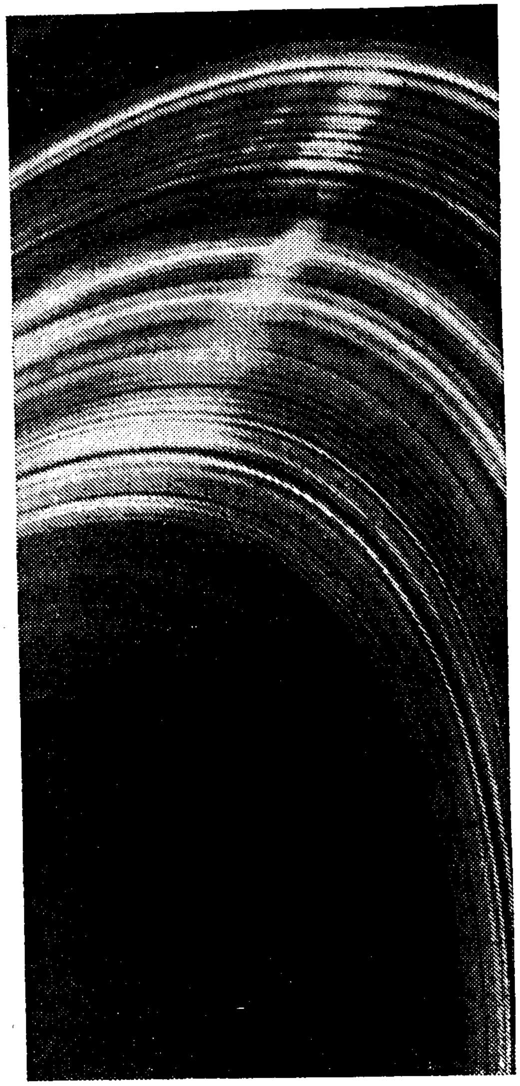

Figure 71b. The same formation; during observation from the opposite side (in the transmitted light) they appear to be light. Photographs from the Voyager 2.

out. The radius of its external boundary comprises about 2.2 R_U which, as we can see, again satisfies the limitation applied by Rosh. In 1978, four more rings were discovered, weaker than the others: ring η between β and Γ and three rings lying inside α and designated with the numbers 6, 5 and 4. In this way, right now a total of nine rings are known on Uranus.

An interesting property of the rings of Uranus was the fact that their width, possibly, varies, that is, there is noticeable eccentricity in it. From a mathematical analysis using equations of focused ellipses, it follows that in the case of coplanar orbits, the value of eccentricity of the ring E can reach 0.13 and if the orbits are not coplanar, then at least at one point width of the ring can return to zero. But if this condition actually occurs, then due to collision of particles of the ring at the zero point it must rapidly expand. Unfortunately, the existing experimental data does not make it possible yet to unambiguously establish the reality of this effect; nevertheless, the theoretically broad changeability of ring shapes is possible.

Attempts have been undertaken to explain the unusual structure of the rings of Uranus and due to the existence in it of six satellites found distances of 68,000 km (2.68 R_U) from the center. However, this has not been successfully discovered.

Very little is still known about the nature of particles of the rings. It is possible only to assume that the dark particles forming them most likely are not ice. Starting with an analysis of the dynamic properties of rings, Van Flendern put forward a hypothesis that they have formed not from solid particles but from clouds of gas. However, such clouds must rapidly scatter in space if there is no kind of constant source of gas emitted in order to compensate for this scattering. Therefore, at the same time, they postulate filling by the reserves of gas from the satellites or even the existence of invisible satellites on the orbits of the rings. Both these hypotheses seem, in our opinion, fairly artificial as an exemplary analogous hypothesis explaining the structure of the rings of Saturn by the presence of asteroid-like blocks as put forward by V. D. Davydov. /181

The question continues under discussion as to whether or not Neptune has rings. Several years ago, the existence of a ring was reported jointly by the colleagues of American astronomer E. Gaynan who had observed back at the end of the 1960's a change in brightness of one of the stars when it was covering Neptune. The measured course of incidence of brightness was impossible to explain as a satellite (then the incidence has been stronger and sharper) and therefore a hypothesis was put forward about rings located very close to the planet within limits 3600-7900 km from the edge of the disk. Moreover, another American scientist D. Elliot who had earlier made a number of observations did not discover rings in the equatorial plane of Neptune (on the level of intensity of particles corresponding to obstacle thickness 0.07, that is, higher than the Jupiter rings), but their existence outside this plane he considers hardly probable basing his conclusion on the existing examples of the rings of Jupiter, Saturn and Uranus. One must truly consider that the position itself of the equator of Neptune is already known fairly precisely (within the limits of a few degrees). In 1981, a report was put out on the discovery for Neptune of a third satellite found at a distance close to the planet. However, it was not a satellite that was observed but one of the brighter formations of the ring which was found after a new series of observations in 1984 called an "arc" or "segments." The nature of this segmentary structure still remains disputed. Although the hypothesis itself about the rings (at least such weak rings as those of Jupiter) began to be more plausible. But in this case, the theoreticians first of all had to find an explanation for the phenomenon as to why at a distance of $\approx R_N$ where the arcs of rings were discovered, that is, beyond the Rosh limit, combining of particles formed there into a single body did not occur (agglomeration) inasmuch as here the force of gravity predominates over forces caused by tidal perturbations in the field of gravity of Neptune.

The horse
said,
looking at a camel:
"What kind of a giant mongrel horse are you?"
The camel cried:
"Are you actually a horse
You are just
an undeveloped camel."

V. Mayakovskiy
"Poems for different tastes"

CHAPTER IV
THE INNER STRUCTURE AND THERMAL HISTORY

The development of the modern appearance of planets and satellites was directly related to processes occurring in their interiors and in the final analysis was determined by certain common principles and stages of chemical evolution of planetary matter. At the present time, it is difficult to give unambiguous answers to questions about what the sequence of these stages was. Moreover, already experimental data accumulated which satisfy theoretical models make it possible to put forward a number of basic hypotheses relative to the geological present and past of the planet and to understand the special features of their inner structure. /182

Consideration of the structure and chemical composition of the planet-giants brings us to the present stage of formation of the solar system about 4.6 billion years ago. We will start with the basic concepts of the fact that the primary composition of matter of a protoplanetary nebula was the same in all of the fields it occupied and corresponded to the solar or the cosmic incidence of elements. It is known that in the incidence of elements, besides small exceptions, one observes a fully definite principle: with an increase in the atomic order number it exponentially decreases (down to $z = 40$) and for heavier elements the value of incidence is retained almost constant.

In the composition of matter of the Sun, planets and meteorites, basic groups of elements have entered formed according to the modern concepts in galactic nuclear synthesis (nucleo-synthesis) no less than 10 billion years ago. With the possibility of nucleo-synthesis, /183 right now such processes as occur in the central fields of explosion during flares of supernova stars and during ejecta of matter from an unequal layer of neutron stars in close dual systems are involved. Then, the formation of elements heavier than iron occurs as a result of capture of neutrons and subsequent β-decay. The corresponding concepts are developed by Soviet astrophysicists of the Ya. B. Zel'dovich school.

In the process of formation of the solar system, possibly, natural synthesis continued of certain radioactive and stable chemical elements whose path of evolution is reflected in the incidence and relationship of isotopes. Figure 72 shows a graph corresponding to

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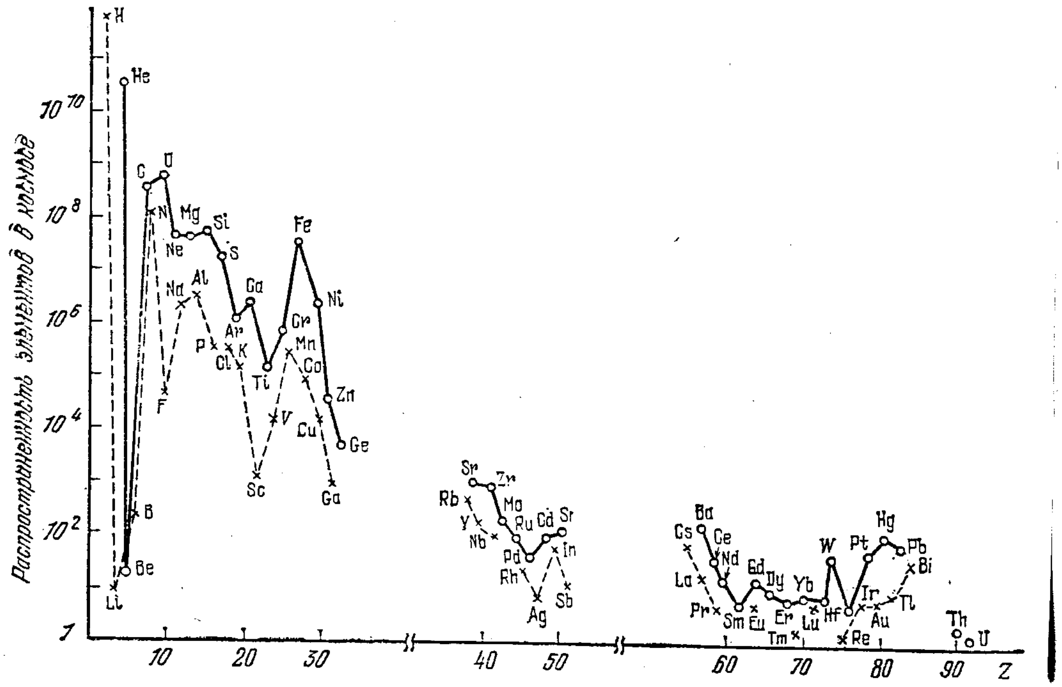


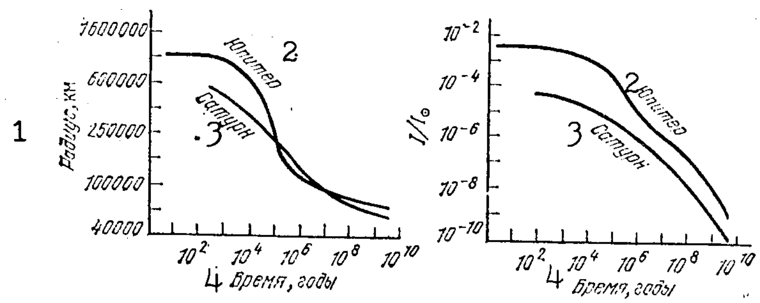
Figure 72. Cosmic incidence of chemical elements (according to D. Ross and L. Aller). The solid curve separates elements with an even atomic number Z, the dashed lines -- with an odd number.
Key: a. incidence of elements in space.

the chemical composition of the Sun according to results published in 1976 from research by American cosmochemists D. Ross and L. Aller who made more precise the conclusions relative to the incidence of elements found earlier, in particular, the results broadly used from G. Zyuss and G. Yuri obtained in 1956. It is not difficult to confirm that when describing this chemical composition of the universe, about a dozen elements are the most important, among which a predominant role is played by hydrogen and helium. Along with neon, they form a more volatile group of substances (the gas component). Less volatile are water, ammonia and methane, which belong to the ice component and the nonvolatile substances (metals, silicon and their oxides) form the heavy (or as it has already been called, the "rock" component entering into the composition of the rock.

Hydrogen and helium are used as the basic "construction material" of our solar system, primarily being, as they say, a rotating gas-dust disk from which the central fragment -- the Sun was separated. The dust component of this disk formed heavy and ice components. Later on, the heavy fraction of elements of the solar composition was retained in the form of planets of the Earth group (after a loss by these planets of the volatile components) and in the form of larger nuclei of planet-giants surrounded by ice mantles and with massive hydrogen-helium clouds maintaining them. Then the relative content of the heavy and ice components, obviously, did not increase in mass by a few percent in the entire area of formation of the planet.

But the significant evaluation as to how all of the hydrogen was dissipated from Jupiter or Saturn would require a time significantly exceeding the age of the solar system. On Uranus and Neptune, with a weaker maintenance of light volatile elements, due to the small mass of these planets, one observes an increase in the relative content of the heavier elements and, corresponding to Uranus and Neptune, they possess a more average density in comparison with Jupiter and Saturn. A significant role here can be played by the circumstance that in the nuclei of Jupiter and Saturn an accumulation of the main part of hydrogen and helium occurred from the environs of the protoplanetary nebula as a result of which Uranus and Neptune appear to be a combination of these elements. Jupiter alone "gathered" such a quantity of matter that its mass is two and a half times greater than the total mass of all of the remaining planets. At the same time, with lower temperatures in the fields of Uranus and Neptune, ammonia and methane were condensed more effectively on them. It is possible, therefore, to think that the giant planets passing through the evolutionary process of compression underwent the least change in the time of accumulation. /185

The process of compression of Jupiter and Saturn from the moment the initial phase was completed, encompassing the first approximately 10 million years up to modern dimensions, according to the theoretical model by A. Cameron and D. Pollack is shown in Figure 73. For the



Key:
1. Radius, km
2. Jupiter
3. Saturn
4. Time, year

Figure 73. Evolution of dimensions and illumination of Jupiter and Saturn from the moment of beginning accumulation to the present time. On the left -- the progress of compression; on the right -- a decrease in illumination of the planet I relative to illumination of the Sun I (according to D. Pollack and A. Cameron).

time which has passed from the beginning of formation, the primary cloud of gas decreased by approximately a magnitude of three from which more than two magnitudes came in in the initial phase. It is most probable that the transformation occurring in the modern epoch releasing or compressing gravitational energy into thermal causes an excessive radiation of these planets in comparison with the energy received from the Sun -- approximately 2-2.5 times for Jupiter and almost 2 times for Saturn. The required value of compression of Jupiter comprises then about 1 m/year. As a result, there is an /186 increase in measured brightness temperatures over the equilibrium (effective) temperatures calculated from conditions of balance brought to the planet by solar energy and energy emitted to it in the surrounding cosmic space.

The calculation mode of changing the value of radiation in the process of evolution also is shown in Figure 73, from which it is apparent that at an early stage of formation the illumination of Jupiter could reach tremendous values: about 1% of the illumination of the Sun! It is possible therefore to think that due to the rapid compression high temperatures of the interior of these planets developed and the excess of radiation observed involves not the separation of gravitational energy, but that continuing from their cooling in the present epoch. From the other hypothetical sources of energy, for explaining this phenomenon, there is also interest in the possibility of heat generation as a result of the continuously occurring transition of molecular hydrogen to metallic or the incidence of helium from a hydrogen-helium solution due to its immiscibility with metallic hydrogen, with subsequent drift to the center of the planet: as calculations have shown, such chemical differentiation and "outflow" of helium inside from the outer molecular fields are capable, in principle, of providing the required value of energy generated in the interior. Let us remember that with this process one can relate such deviations in the shapes of Saturn from the equilibrium and the mechanism of pumping energy found in resonance to the dynamic system of the rings.

On the other planets located much closer to the Sun and having significantly less mass, the loss of the volatile elements themselves -- hydrogen and helium and also easily boiling compounds such as methane, ammonia, water, occurred already in the stage of accretion or soon after completion of its basic phase. Both the low cosmic /187
velocity and the much higher effective temperatures of which it was capable were incident inversely proportional to the square of the distance from the Sun. As was already noted, temperature and pressure of the solar radiation can noticeably affect the composition itself of the protoplanetary cloud by fractionation of the primary matter due to sweeping out of part of the volatile elements from the area of formation of the Earth planets. Moreover, at great distances where the giants formed, an additional decrease in temperature (right down to the temperature of condensation of gases) could have occurred, due to screening of solar radiation by the dust component of a primary cloud down to the moment of its disappearance.

Models of Planet-Giants

The mechanical properties considered above of the planets -- mass, dimensions, special features of shape and a rotational movement -- are the most important consequences for problems of their internal structure. The distribution of mass in the interior of the planet determines its gravitational potential and the moment of inertia. The actual gravitational potential is distinguished from simple Newtonian potential described as the spherical-symmetrical distribution of density depending on the radius and can be presented in the form of an expansion according to spherical function. The main member of the series corresponds to the potential of attraction of the sphere with mass equal to the mass of a planet and members of the second and higher orders (the so-called zonal and tesseral harmonics) reflect the details of its internal structure.

The even and odd harmonics take into consideration, respectively, the deflection and distribution of density from the spherical-symmetrical and the hydrostatically uniform. They are characterized by multipolar moments J_n determined according to the value of perturbations of orbit of natural and artificial satellites and the trajectory of moment of flight spacecraft. The basic contribution is made by the first correcting member of the second magnitude, proportional to the quadripolar moment J_2 which takes into consideration the compression of the planets. Correspondingly, J_2 defined as $J_2 = \frac{C - A}{MR_E^2}$ has a magnitude of compression α (all of the symbols are presented on pages 30-48). The subsequent zonal moments /188 in the body found in hydrostatic equilibrium decreased proportionally to the second and subsequent degrees of compression. At a value of moments higher than J_4, the internal layers of the planet are basically effective, therefore they speak much less about its internal structure.

Another important parameter is directly related to the moment J_2; it reflects the course of change of density with depth. This dimensionless moment of inertia $I = \frac{\bar{I}}{M\bar{R}^2}$ expressed as the average moment of inertia in the form $\bar{I} = \frac{C + 2A}{3}$ and the average radius $\bar{R}$ or in simplified form, by the moment of inertia relative to the polar axis and the equatorial radius R_E, that is, $I \approx \frac{C}{MR_E^2}$ (see Table 1). In a case where density in the entire thickness is retained as constant (model of a uniform sphere), $I = 0.4$. If this density increases with depth, then $I<0.4$ then the opposite case $I>0.4$. For instance, for Earth, the experimental value $I = 0.3315$ corresponds to a significant growth in density toward the center which in actuality occurs inasmuch as the solid component is basically concentrated in the nucleus.

The multipolar moments apply limited conditions on the position of the equipotential (level) surfaces calculated in the theory of the figure of gravitational bodies and particularly widely used during calculations of models of the inner structure of giants. In planets found in a state of hydrostatic equilibrium, the equipotential surfaces are characterized by uniform values of pressure P, density Γ, temperature T and other thermodynamic characteristics of matter. As to the degree of deviation from hydrostatic equilibrium, it is possible to judge according to the value of the first odd moment J_3. For Earth, it unexpectedly turned out to be fairly large, on the order of the square of compression. This is evidence of the divergence of the shape of Earth from equilibrium (for a value on the order of $\overline{R}\alpha 2$ on the surface) and the presence in its interior, besides the radial stresses caused by pressure, of tangential stresses. Their value is several magnitudes smaller in comparison with the radial comprising, nevertheless, several dozens of kilograms for each square centimeter.

At the same time, the large planets primarily gas-liquid Jupiter /189
and Saturn, in their composition, are closest to hydrostatic equilibrium. In their gravitational potential, one does not detect any kind of noticeable contribution from the moment G_3 according to results of measurements made on the Pioneer and Voyager spacecraft. Here excess radiation of energy is indicated as a result of thermal flow from the interior. A decisive role has to be played here by convective thermal transfer and not a significantly less effective mechanism for molecular heat conductivity: it is easily shown that on the characteristic dimension of the magnitude of the radius of the planet, the role of its mechanism is negligibly small and can have a certain contribution in cooling only in the very outer regions. The basic shift, obviously, occurs within the limits of separate shells due to differences in density of matter although the precise boundary of the section between them possibly does not exist. Moreover, on Jupiter and Saturn, a certain reliable effect of the gradient of concentration of helium by altitude can be created related to the mechanism mentioned of its release from the hydrogen-helium solution.

As to the convective activity of the interior, we are also talking about the presence in Jupiter and Saturn of the appropriate magnetic fields in whose formation, obviously, not only the central field but also the shells positioned close to the surface participate. Along with the theories which have received more recognition of the planetary magnetic dynamo, as the alternative mechanisms for generation of a magnetic field, we are looking at movement which induced precession of the axis of rotation of the planet and excitation of the thermoelectric electromotive force with convective transfer onto the boundaries of the field from several different chemical compositions.

The intensity of the magnetic field of Jupiter at the equator according to the measurement data from the Pioneer and Voyager spacecraft comprises 4.2 oersteds (E) which is almost a magnitude greater than the intensity of the magnetic field of Earth. The polarity of it is inverse to the polarity of Earth's field, that is, the northern and southern magnetic poles are found in the same hemispheres as the corresponding geographic (more precisely Jovian-graphic) poles and not in the opposite hemispheres as occurs on Earth. /190
The value presented for intensity of the field is related to its basic dipolar component; along with it, the noticeable components observed with higher magnitude -- the quadripolar and octipole components whose relative contribution in value is approximately the same relative to the contribution of those same components in the geomagnetic field. The axis of the magnetic dipole of Jupiter does not coincide with the axis of rotation and the center of the dipole is shifted relative to the center of the planet into the northern hemisphere. Therefore, on

the poles, the intensity of the field varies: on the north pole, it comprises 14 E and on the south pole, 11 E.

The intensity of the magnetic field of Saturn was considerably smaller and in good agreement with the value indicated by the Soviet scientist Sh. Sh. Dolginov on the basis of the mechanism of generation of a field as a result of precession. According to the data of measurement from the Pioneer 11 spacecraft, it comprises on the equator 0.2 E, on the poles 0.56 E; the polarity of the field also is opposite that of Earth and the angle between the axis of the dipole and the axis of rotation is smaller than 2-3°. Data on the presence of magnetic fields on Uranus and Neptune still have not been conclusively confirmed.

Significant progress in modeling the structure of giants has been facilitated both by the new data of observations and the development of the theory of the shape of gravitational bodies and by successes in high pressure physics. The latter involves primarily making the equation of state more precise which determines the dependence of pressure P on density and temperature T, $P = P(\rho, T)$ for hydrogen and helium and also for heavy and ice components with high pressures and temperatures inasmuch as the equation of state of real gas is applicable for calculations only of the most outer fields. Besides the fact that the change of pressure of the medium functionally depends not only on the change in temperature and density, but also on the concentration of components (which in itself is very complicated for a description of its thermodynamic state) a theoretical description of the conditions of formation and stability of phases at high pressures and temperatures is a complex independent problem. Matter acquires then unusual properties, for example, the transition of hydrogen into a metallic state. This transition occurs in conditions of very high pressure when the external atomic shells seem "depressurized." The density of the metal hydrogen can be evaluated roughly assuming that the distance between protons is on the order of Bohr's radius $a_0 = \hbar^2/me^2 = 0.529 \cdot 10^{-8}$ cm (here m and e are the mass /191
and charge of the electron, $\hbar = h/2\pi$, where h is Planck's constant). Inasmuch as the mass of a proton $m_p = 1.67 \cdot 10^{-24}$g, we find $p \approx m_p/a_0^3 \approx 10$ g/cm^3. In this way, this estimate appears almost a magnitude higher: more strict although not very reliable calculations show that with pressure 2.6 millions of atmospheres (2.6 megabars, or the abbreviation Mbar), the metallic hydrogen is found in thermodynamic equilibrium with molecular hydrogen and its density equals 1.15 g/cm^3. For transition of helium to a metallized state, one requires a pressure of about 90 Mbar which is not achieved inside Jupiter. With the presence of an extensive layer of conducting metal hydrogen, a large value of magnetic moment is definitely related in this very large planet of the solar system.

Data on the behavior of matter in extreme conditions are based on concepts of statistical physics and quantum mechanics. In a very general case, the thermodynamic state of the liquid and metal hydrogen, ice and matter of mountain rock at great depths is described by the equation of state in the so-called Debye approximation with the well-known or additionally calculated relationship to the density of the characteristic (Debye) temperature θ. This temperature is expressed in the form $\theta = h\nu/k$, where ν is the maximum frequency of oscillation of atoms of the crystal extending along it in the form of waves, each of which can be represented as a quasi-particle -- a quantum of oscillation movement or a phonon. The product $k\theta$ (k is Boltzmann's constant) characterizes in this case the energy of the shortest wave phonons in matter.

The concept of the phonon makes it possible to study thermal and other properties of solid bodies and matter found in the field of super high pressures using methods of the kinetic theory of gases. During calculations of the deepest layers where temperature reaches dozens and more than thousands of degrees Kelvin, sometimes high-temperature corrections are introduced which take into consideration the apparent deviation of oscillation of atoms in crystals from a quasiharmonic approximation and also the effect of thermally excited electrons of conductivity. In the quasiharmonic approximation, one more variable is introduced which is extremely important for calculation of models of the inner structure -- the so-called Gruneisen parameter which characterizes the change of frequency of /192 oscillation depending on density. Along with the Debye temperature, it fully determines the thermodynamic state of the matter for the appropriate model of a solid body.

Inasmuch as pressure rapidly increases with depth, the hydrogen and helium making up the inner shells of large planets are found in a critical state. The critical values of pressure and temperature which are physical and chemical constants of matter equal for hydrogen, 12.8 atm and 33 K and for helium 2.3 atm and 5 K. For pressure below critical, the mixture falls into two equilibrium phases -- liquid and vapor and with pressure higher than critical a continuous transition of the gaseous phase to liquid occurs, the physical distance between the phases disappears and the mixture becomes uniform. It is not difficult to see that the gaseous clouds of these planets must have a small incidence and these clouds can belong to the atmosphere.

Temperature and pressure determined at levels of atmosphere where the intrinsic and reflected radiation of the planet form are used as the necessary boundary conditions and calculations of models of the inner structure providing initial values for extrapolation of thermodynamic parameters inside. The lower boundaries of temperatures in the interiors give extrapolation according to the isotherm (cold models) and the upper boundaries -- extrapolation according to the adiabatic (hot models). These two models can be considered as maximum inasmuch as it is difficult to achieve the presence of a super adiabatic gradient of temperature in conditions which do not prevent shifting. The most positive result which establishes the probable range of parameters in the central region leads to adiabatic extrapolation. Its basis in the assumption, primarily for Jupiter and Saturn, is strengthened as we have seen by fairly reliably established facts that both these planets are found in convective equilibrium.

The change in thermodynamic and aggregate state by depth makes it possible to trace the indices of the polytrope and phase diagrams for the hydrogen-helium solutions determined depending on partial pressure of components and temperature. In the majority of models, the assumption is used that the chemical composition of Jupiter and Saturn correspond to the solar, that is, to the relative content of /193 helium according to a mass of about 20% or one atom of helium to approximately 20 atoms of hydrogen. The data of measurements of content of helium and the ratio He/H_2 in the atmosphere of Jupiter and also the satisfactory agreement obtained between calculated parameters of the figure with the observed parameters led up until recently to the conclusion that this composition actually gives the best results and the components are heavier than hydrogen and helium, practically having no effect on the internal structure. Moreover, as later calculations have shown, the situation obviously is more complex. With a solar ratio of content of hydrogen and helium, one can assume the presence on Jupiter of a comparatively large nucleus consisting of heavy and icy components and also add water to the shell which on Jupiter, according to estimates is approximately 15 times larger in comparison with its abundance in the matter of the solar composition (or, in absolute content of $\approx 1.8 \cdot 10^{29}$ g which corresponds approximately to 30 masses of Earth). At the same time, the ratio of total content of water to the heavy fraction of matter of the nucleus of Jupiter strongly depends on the initial value adopted of temperature T_0 on a level with pressure at 1 atm from which extrapolation is made by depth: with an increase of this temperature, the mass of excess water increases sharply and the mass of the nucleus decreases. The abundance presented above of H_2O corresponds to the value $T_0 \approx 190$ K which, possibly, is somewhat high. As to Saturn, as we see from the models, it has a basic mass of water along with methane and ammonia concentrated in the ice shell directly next to the nucleus.

If these results later on are confirmed, they will have an important value for the best understanding of the special features of the early stage of evolution of large planets. They can be looked at as an indication that at the accretion stage, the mechanism of separation of phases is in operation which separates water, ammonia and methane from the heavier fractions and its effectiveness would be higher the lower the temperature is in the fields of formation of the planet. Therefore, extensive ice shells were formed on Uranus and Neptune, on Saturn it remained relatively small and on Jupiter subjected to a more high-temperature (among the planet-giants) phase of evolution, was not retained in general transferring to the form of a mixture in a basically hydrogen-helium solution. These discussions, of course, have a qualitative character, but unfortunately, right now we do not have more reliable data available. /194

Quantitative estimates of the ratio of the content of concentrated components in the core and the mantle are complicated by the fact that the mass of the nucleus, generally speaking, hardly affects the value of gravitational moment with which the results of the calculations are compared. One must add to this that with the retained indeterminancy of the equation of state of molecular hydrogen, it is possible to satisfy the limitation applied to these results and without using assumptions about the increased content in the mantle of components heavier than helium such as water. Definite possibilities are related here by a number of scientists with a fuller analysis of the thermodynamics of molecular hydrogen, in particular, with a calculation of the degree of solubility of helium and metallic hydrogen at high temperatures and pressures. It would seem that today the most real is an estimate of relative value of the nucleus on the order of 3-4% of the mass for Jupiter and 20-25% for Saturn. The masses of the cores of Uranus and Neptune along with the ice shells in the calculated models reach a relative value of 85-90%. One should note that the new values of the period of rotation of these planets (see Table 1) lead to a much better agreement with such models of the values of the quadripolar moment α_2 determined according to perturbations in the movement of the satellites of Uranus, Ariel and Miranda and the satellite of Neptune, Tritan, although in the estimates of these values, they all still retain a considerable spread.

Adiabatic models of the inner structure of the planet-giants responding to the modern concept of a multilayer differentiation of matter, for examples of Jupiter and Uranus, are shown in Figure 74. A

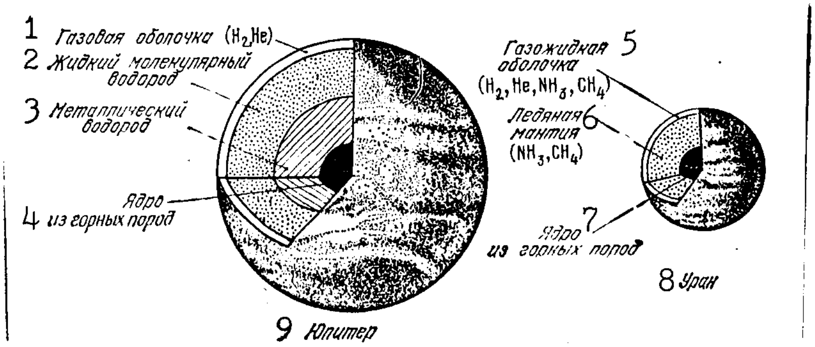


Figure 74. Models of the inner structure of Jupiter and Uranus. Key: 1. gaseous shell (H_2, AG); 2. liquid molecular hydrogen; 3. metallic hydrogen; 4. nucleus of rock; 5. gaseous shell (H_2, AG, NH_3CH_4); 6. ice mantle (NH_3CH_4); 7. nucleus made of rock; 8. Jupiter; 9. Uranus.

significant part of the inner fields of Jupiter and to a lesser degree Saturn are made up of conductive metal hydrogen. The intermediate shells of Uranus and Neptune (and probably, the shell of Saturn adjacent to the core) consist of hydrogen compounds which are a mixture of water and ammonia-methane ice.

The content of hydrogen in an unbonded state on Uranus and Neptune is considerably less than on Jupiter and Saturn. The large extent of the zone of solid matter (no less than 3/4 of the radius) /195
brings these planets close to planets of the Earth group. Moreover, it is possible to propose that due to the low viscosity of ice for Uranus and Neptune, mechanical concepts of the model of a gas-liquid

planet are used found in a state of hydrostatic equilibrium. The most outer shells located over extensive layers of solid and liquid matter are comparatively thin layers formed basically by gaseous hydrogen and helium.

In the development of the concept of gas-liquid planet-giants, in the study of the equation of state of matter at high temperatures and pressure, the theory of figures and calculations of modern models of their inner structure has received a significant contribution from the Soviet geophysical school. We will present the values of the basic parameters in the core of planet-giants according to the model developed by V. N. Zharkov, V. P. Trubitsyn and their coworkers.

The temperature and pressure in the nucleus of Jupiter with the ratio He/H is close to that of the solar and appears to equal $T \approx 25 \cdot 10^3$ K and $P \approx 80$ Mbar, and in the nucleus of Saturn $T \approx 20 \cdot 10^3$ K and $P \approx 50$ Mbar. The transition of hydrogen to Jupiter in a critical gas phase occurs at a level of $\approx 0.98\ R_U$ and transition to a metal phase -- at the level approximately $0.76\ R_U$ with pressure $P \approx 3$ Mbar and temperature approximately 10,000 K. Obviously, the jump in density then does not occur due to lack of continuity of the process of metallization in the liquid hydrogen. The metallic shell extends to the boundary from the nucleus at a level of $0.5\ R_U$. In the model of /196
Saturn, the metallic hydrogen is formed beginning with a level ≈ 0.46 R and fills the layer approximately to 0.27 R where the nucleus begins. Pressure on the surface of the Jovian nucleus is estimated to equal ≈ 45 Mbar and on the surface of the nucleus of Saturn -- about 10 Mbar. The adiabatic models of the inner structure of Uranus and Neptune in which the initial state of elements corresponds to cosmic propagation, and relative content of hydrogen and helium remain no more than 5-8% by mass leads to values of temperature and pressure: at the center of Uranus $T = (10\text{-}12) \times 10^3$ K and $P \approx 5.5\text{-}6$ Mbar, and at the center of Neptune $T = (12\text{-}14) \cdot 10^3$ K and $P \approx 7\text{-}8$ Mbar. The boundaries of their extensive ice shells (cores) begin with a pressure of about 100 kbar.

The Matter of the Planets in the Earth Group and Meteorites

The inner structure of planets of the Earth group, as a result of any predominant element composition and conditions of formation differs from the planet-giants by the presence in the entire thickness of the matter of rock with partially melted mantle and solid crust on whose surface one can find traces of the geological history of the planet. The difference in densities of this group of planets (see Table 1) along with the results of modern calculations leads to concepts of nonuniform chemical composition of primary matter as a result of fractionation of elements not only in the entire protoplanetary nebula but also in limits of 1-2 IAU. We are talking primarily about the metal-silicate fractionation due to the presence of temperature of condensation of hot gas of solar composition resulting in nonuniform content of iron and silicon at different distances from the Sun. Here the supply of diffractionation of iron and sulfur (more precisely, groups determined by them of the so-called siderophile and chalcophile elements). Corresponding to the increase in heliocentric distance, the difference in chemical composition of the primary matter from the composition of iron meteorites has grown due to the large oxidation of iron (with the formation of silicates) and simultaneously the increased content of the sulfide part in it. Here it is possible to consider a certain analog with a degree of fractionation of the heavy and ice components depending on the distance from the Sun: the latter has a lower temperature of /197 condensation and therefore comprises the basic portion of mass of the distant planets themselves and their satellites.

Then, the relatively small quantity of matter of the protoplanetary nebula from which planets and asteroids in the nearest environs of the Sun were formed, in their composition, obviously, corresponded to the composition of meteorites -- namely therefore they were compared with them speaking of fractionation of primary matter. These space wanderers contain information about the initial stage of nucleation of the large bodies about 4.6 billion years ago: such is the age of the overwhelming majority of meteorites which have been incident on Earth determined according to the isotopic ratio of lead Pb^{207}/Pb^{206} and strontium to rubidium Sr^{87}/Rb^{87} and at a later time also the method with greatest precision, according to the ratio of samarium and neodymium. Right now there is no doubt that meteorites formed as a result of crushing at the beginning of larger bodies and therefore they can be looked at as fragments of asteroids.

It is well known that depending on the ratio of two basic phases -- metallic (iron-nickel) and rock (silicate) -- the meteorites are divided into three general classes: iron, iron-stone and stone. In the first of these, a first phase predominates (up to 94%, including Fe and Ni both in a free and in a bonded state) and in the latter -- a secondary phase (up to 80%) and in the iron-stone there is approximately a uniform quantity of iron silicates. Besides these two basic phases, in each class of meteorites also a sulfide phase or a troilite phase is present entering the composition of sulfuric iron (troilite) and a number of other rock-like minerals.

In extent (frequency of incidence) the class of rock meteorites significantly predominates -- higher than 90% in relative number whereas the frequency of incidence of iron meteorite does not exceed 6%, the iron-rock is 1.5%. Among rock meteorites in whose composition mainly there are lithophilic elements forming stable natural compounds with oxygen (sodium, potassium, magnesium, aluminum, silicon, calcium, and, of course, oxygen) the main position is occupied by the chondrites. They were given this name due to the spherical particles contained in their structure, particles with a diameter on the order of 1 mm -- chondrules consisting of silicate minerals. Other /198 meteorites of this class (achondrites) are approximately a magnitude smaller and in their texture (blurring of boundaries between chondrules and the matter mixed in) one can assume that during its formation, they were subjected to a much stronger heating than were the chondrites.

The content of the richest and most chemically active elements -- hydrogen, carbon, oxygen, magnesium, silicon, sulfur and iron depend on variations in temperature and pressure in the primary chemically uniform protoplanetary disk (Figure 72). With an increase in temperature, the relative content of iron must increase as a result of loss of silicates and predominance of reducing processes over oxidating processes due to loss of volatile elements. The ordinary chondrites enriched with iron form group H and those poor in iron, group L. Enstatite chondrites consisting basically of a mineral from the magnesium silicate family -- enstatite ($MgSiO_3$) and nickel iron possess the highest degree of reduction; but the highest degree of oxidation belongs to a group of carbonaceous chondrites or group C in which almost all of the iron is bonded in magnetite (Fe_3O_4). The latter, as was noted, are distinguished also by a very high content of volatile elements and are of particular interest.

Actually, if we compare their composition with the combination of the incidents of chemical elements according to the curve in Figure 72, then it is possible to confirm that it hardly differs at all from the composition of the solar matter except for very volatile (atmophile) elements which include hydrogen, nitrogen and inert gases. This gives us the basis for considering that carbonaceous chondrites are closest to the primary chemical mixture from which later on planets of the Earth type and asteroids were formed. The meteorites of this group containing a dark carbonaceous substance, as was already noted, have a very low albedo. The observations indicate that this albedo (≈5%) has a majority of objects in the asteroid band although one would hardly think that their composition is close to that of carbonaceous chondrite. More likely, the matter of this composition covered only their surface if one takes into consideration that carbonaceous chondrites comprise only a small portion among chondrites and meteorites of other classes. Such a hypothesis easily explains the reason why only a small number of asteroids, in their /199
reflective properties, correspond to a composition of the more widespread iron-rock meteorites. The consideration made convinces us that chemical classification and the structure of meteorites is directly related to their origin. In the first place, the total genealogy of meteorites and asteroids makes it possible to propose that the continental bodies themselves are found in different degrees of evolution, depending on dimensions. If the chondrites originated from comparatively small chemically undifferentiated bodies which formed by condensation of primary matter at different distances from the Sun, then the iron meteorites and achondrites, in all probability, are fragments of larger asteroids whose matter underwent a process of differentiation in their nuclei. A certain part of the iron meteorites could, however, occur directly as a primary product of condensation from the gaseous phase of iron in a protoplanetary nebula which the foremost Soviet geochemist A. P. Vinogradov was the first to point out. Secondly, according to the degree of oxidation of iron contained in the meteorites, one can judge the conditions of condensation, primarily temperature, in different parts of the protoplanetary nebula. It is possible to think that the iron meteorites and enstatite chondrites which differ in a greater degree in reduction, were formed primarily at high temperature in nearest distances to the Sun within limits approximately of the orbit of Mercury at the same time that maximum oxidation of carbonaceous chondrites occurred at significantly lower temperatures primarily for

the orbit of Mars. The overwhelming majority of asteroids in the asteroid band and the nuclei of the planet-giants were formed from chondrites. The mixture of metal oxides and hydrated silicates making up the group of carbonaceous chondrites, probably, were in a large ratio in composition of the heavy components of this planet (or as we have already said, the matter of rock). The conditions of condensation predetermined also the difference in composition and average density of the Earth group of planets and this means the course of their subsequent thermal evolution.

One should note that in explaining the path of formation of the matter of chondrites, as the reason for the well-known isotopic anomalies in their composition, there is still no unified opinion. In particular, the condensation model does not explain the presence of grains of hard-to-melt metals and minerals in the chondrites, whose related bodies are found at distances 2-4 IAU from the Sun where /200 temperature, probably, did not reach high values. Attempts have been made to get around these difficulties, starting with a model of sequential condensation with movement of matter of the preplanetary nebula from the hot region of the protosun to the periphery of the solar system. But essentially we are talking about a model of compression of solar nebula of subsequent "spreading" of matter from the protosun inside the accretion disk as is shown in Figure 9 by the arrows. Such a model was proposed and studied by T. V. Ruzmaykina and later was considered by P. Kassen and A. Summers and the mechanism of sequential condensation was developed in part by M. N. Izakov. It is important to note that it applies a condition to the maximum value of full rotational moment of the protosolar nebula of no more than $\approx 10^{52}\ g \cdot cm^2 \cdot s^{-1}$, which, on the whole, can agree with modern cosmogony theories.

Thus, we see that the basic chemical transformations of primary matter occurred at relatively high temperatures in the closest environs of the Sun. Then the most important role was played by the oxidation-reduction processes at the same time that at great distances from the Sun at low temperatures of reaction, they were slowed down and the composition of primary matter, obviously, remained almost unchanged. In the composition, the high-temperature fraction of condensed solid particles from which the planets of the Earth group were accumulated, there were radioactive elements which served as a source for subsequent heating. Therefore, it is just on these planets that the most grandiose changes occurred in the process of evolution leading in the end to differentiation of the component matter and the formation of secondary gas shells -- the atmosphere.

Unfortunately, a strict quantitative basis for all these complex processes using methods of theoretical modeling is complicated by a lack of knowledge of many of the initial conditions of the evolutionary process such as the initial masses and moment of the protoplanetary nebula, the distribution of temperature and concentration of the components, the value of pressure at which the primary condensations of solid bodies occurred, the rate of chemical reactions and intensity of shifting of matter after completion of accumulation, the velocity of degasification from the interior and the effectiveness of bonding of gaseous components with solid matter, etc. Moreover, the study of the inner structure itself of planets in the Earth group, to a well-known degree, is made easier by the presence of its own type of standards in the form of Earth and the Moon for which a powerful method of studying their interiors is available according to distribution of the rate of propagation of seismic waves. It produces a change in characteristics of elasticity with depth and in this way makes it possible to discover the most characteristic traits of the interior structures of the body determined by chemical composition of matter, its phase state and the thermodynamic parameters. /201

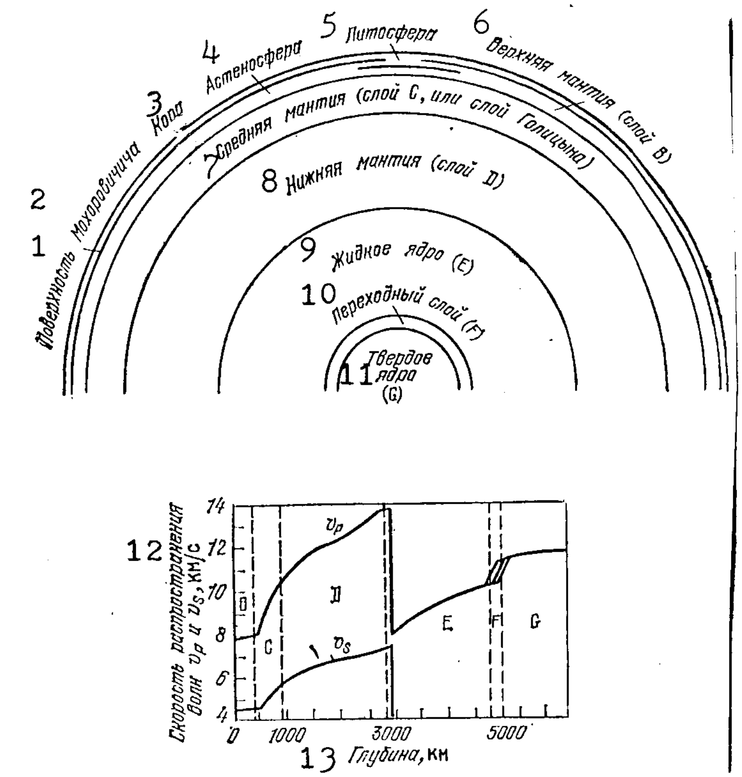


Figure 75. Model of the inner structure of Earth and the rate of propagation of longitudinal (v_P) and lateral (v_S) seismic waves.
Key: 1. surface; 2. Mohorovicic discontinuity [Moho]; 3. crust; 4. asthenosphere; 5. lithosphere; 6. upper mantle (layer B); 7. middle mantle (layer C or the Golytsin layer); 8. lower mantle (layer D); 9. liquid nucleus (E); 10. transition layer (F); 11. solid nucleus (G); 12. rate of propagation of waves v_P and v_S, km/s; 13. depth, km.

Composition and Inner Structure of the Earth and the Moon

Modern concepts about the inner structure of Earth are shown in Figure 75 where the main zones are separated in whose limits a change in the rate of propagation occurs of the longitudinal (P) and lateral (S) waves. Such waves are called bodily waves. They occur in the foci of earthquakes and generate their seismic energy caused by tectonic processes. Penetrating into the depths of Earth, the bodily waves change their velocity, undergo refraction and reflection on the boundaries of the section (shells) with different physical properties. These properties are characterized by the modulus of compression and the shear modulus of matter for the P-waves and also the shear modulus for the S-waves inasmuch as the latter create oscillations only in a perpendicular direction to propagation of the wave (that is, like electromagnetic waves). In liquid media, the shear modulus equals zero and, correspondingly, the velocity of lateral waves also return to zero. From this it is clear that if the medium does not permit transmission of these waves through it, it can be considered liquid. Just such a situation is observed inside Earth on the boundary of the nucleus.

Within the limits of each of the three basic shells of Earth -- crust, mantle and nucleus -- there are a number of additional features which are isolated (zones) with which the change in rate of seismic waves passing through them is related. Therefore, let us look at a cross section of Earth and the properties of zones indicated on the drawing in more detail.

The most upper solid shell -- the crust -- is separated from the layers of the mantle lying below by the boundaries of the sections, with transition through which the rate of the P-wave increases in jumps from 6.7-7.6 km/s to 8-8.3 km/s and the S-wave from 3.6-4.2 km/s to 4.4-4.7 km/s. /202

This boundary is called the mohorovicic surface after the Yugoslavian geophysicist who established its existence in 1909. The Mohorovicic surface (or simply Moho) occurs at various depths due to the difference in thickness of the Earth's crust -- from 30-60 km under the continents to 5-10 km under the oceans. In the axial zones of the middle-ocean ridges, where rift valleys are found, it is maximally close to the surface. As we have already said, the middle-ocean ridges with their rift zones belong to areas of newly formed Earth ocean crust which have lasted into the modern era. In the rift zones are concentrated foci of numerous earthquakes and volcanic activity; and anomalously thermal flow from the interior and a decrease in density of the upper mantle are observed. /203

The Earth's crust formed as a result of partial melting of the matter from the mantle is made up of the set of different minerals consisting of typical lithophilic elements with properties of silicate rock. Predominant (49.13% by mass) is oxygen, entering into the composition of oxides and silicon. After it comes silicon (26%), aluminum (7.45%) and iron (4.2%). These elements have the largest weighted content or, so to speak, the largest clarkes. Percents of elements are named thus according to mass in honor of the American geochemist P. Clarke who first discovered in the 1880's the average chemical composition of the Earth's crust. The predominance of oxygen, silicon and aluminum is caused by the fact that a large part of the minerals belong to the group of silicates alumosilicates, that is, they are salts of silicon and alumosilicon, acids. With the replacement of hydrogen by alumosilicon acids of potassium, sodium and calcium, one obtains the most widespread minerals -- feldspar, in which, in particular, there are the well known sodium-calcium alumosilicates -- plagioclases, and with replacement of hydrogen by silicate acids of magnesium, iron and calcium -- olivine, pyroxene and amphibole. The basis for the crust comprises igneous (magmatic) rock -- basalt and granite. Depending on the content of silicon (SiO_2), they can be divided into acid (more than 65%), average (52-65%) and base (40-52%) and ultrabasic (less than 40%). The magmatic rock is crystallized from alumosilicate melt enriched with gases -- so called after the outstanding Russian scientist V. I. Vernadskiy who first pointed out the similarity in properties of aluminum and silicon geochemical processes and the formation of natural compounds. With an excess of this melt on the surface in the form of lava and intense degasification, extrusive (effusive) basic rocks of the crust -- basalt are formed and with cooling to depth -- the more acid granites, gabbro and certain other varieties of intruded (intrusive) rock. In the basalts, there are primarily such minerals as plagioclase, pyroxene and olivine. Usually there are two basic types of basalt -- toleite, somewhat saturated with silicon and alkaline -- not saturated with it. In its composition, the toleite basalts, obviously, reflect the composition of the upper mantle in the best way in regions where /204 the magmatic activity is apparent. In comparison with basalt, granite contains more silicon and less iron and magnesium. In their composition, feldspar predominates, aqueous alumosilicates (mica) and quartz which is a crystalline modification of (hexagonal and trigonal) silicon.

The intrusive rock partially undergoes change (metamorphosis) under the effect of high temperature and pressure at a depth as a result of which granites form differing from granites of the metamorphic type of rock such as gneiss and crystalline shale. The upper part of the crust is a continuous sedimentary layer consisting of products of erosion from intruded and metamorphic rock and also redeposition involving the activity of the biosphere (limestone, radio laurite). The continental crust under a sedimentary layer is divided into two parts: the granite layer composed of predominantly granite and gneiss and a "basalt" layer deposited under it made up, probably, of more basic (containing less SiO_2) modifications of metamorphic rock. Under the sedimentary layer of the oceans lie basalts which form a layer up to 2 km in thickness and below that gabbro which has the same composition as the basalt but is solidified deeper. The formation of the crust of the ocean type continues at the present time, in the rift zones of the middle-ocean ridges due to differentiation of mantle matter coming into the faults.

Under the crust is the upper mantle (zone B). Its upper layer underlying the crust sometimes is called the substratum. Besides the crust, it forms a lithosphere -- the most rigid shell of Earth, below which one finds close to the melted layer with decreased strength -- the asthenosphere. This is identified partly with the Gutenberg layer in which one notes a noticeable decrease in the velocity of lateral seismic waves. The causes of their slow passage, obviously, are the large geothermal gradient in the asthenosphere and the significant (a magnitude of two or three) decrease in viscosity of matter in comparison with the lithosphere. The lower boundary of the asthenosphere lies at a depth of 250-350 km and its upper boundary is the closest to rising to the surface under the axes of the middle-ocean ridges. With transition to the sea zone called the middle mantle or the Golytsin layer, the velocity of seismic waves increases /205
to a depth of about 1000 km where a boundary of the lower mantle (zone D') is located and in the lower mantle the increase in velocities slows down sharply. Between the lower mantle and the core are small (about 200 km in thickness) transition layer D'' with the additional small increase in velocity of the P-wave.

The increase in seismic velocity in the C zone is due to phase transitions resulting from restructuring of minerals in modifications with denser packing of the atoms. In distinction from the acid and base rock of the crust, the mantle comprises ultra-base rock containing the least quantity of silicon dioxide SiO_2 in the form of minerals and quartz and at the same time a large quantity of magnesium oxide in the composition of several types of minerals. The main rock-forming minerals of base and ultra-base rock (basalts, dunites, gabbro, peridotites, diabases, etc.) are the iron-containing and magnesium-containing silicates -- olivine and pyroxenes which have, respectively, the formulas (Mg, Fe) SiO_4 and (Mg, Fe) SiO_3. Supposedly, the primary mantle of Earth comprises olivine-pyroxene rock (the so-called pyrolite) before differentiation of the component planetary matter.

According to the modern concepts supported by laboratory petrochemical research on minerals with values of the parameters of the Earth interior, olivines in the upper mantle at the boundary of the B and C zones (400-420 km) as a result of polymorphous phase transition deteriorate in the structure of the modified spinel found in the magnesium edge of the olivine series and having a structure with dense cubic packing of oxygen ions. This transition explains the increase at this level of velocities of the P-waves. In turn, the pyroxenes even at a depth of about 70 km are crystallized into orthopyroxene and in the presence of aluminum oxide Al_2O_3 (alumina, corundum) transfer to granite and the quartz -- sequentially in the structure of coesite and stishovite -- a mineral which is 62% denser than ordinary quartz. In the middle mantle, beginning approximately at a depth of 700 km, it is assumed that there is one more phase transition from the spinel zone to the zone of perovskite -- a mineral which has a clearly pronounced cleavage into cubes, that is, a particularly dense cubic packing. Here the structure of the corundum can be rearranged into a structure of ilmenite replacing atoms of /206
aluminum with atoms of iron and titanium. In the uniform D layer, obviously, there is a whole perovskite zone and the velocity of seismic waves increases (although with a lesser gradient) only due to compression of matter under pressure of the layers lying above and an increase in its density.

In zone E, the velocity of longitudinal waves decrease approximately by two and the lateral waves do not penetrate completely through this layer. At the same time, again they are excited in the central part (zone G) separated from E by the small S layer with thickness about 150 km where one notes a small increase in velocity of the P-waves. These facts give us the basis for identifying the E layer with the upper liquid nucleus with radius about 3460 km and the G layer with the internal solid (or more accurately, partially melted) nucleus with radius 1250 km. The mass of the entire nucleus comprises about 30% of the mass of the entire Earth at the same time that the mass of the inner nucleus is 1.2%. Such a distribution of mass in Earth as a whole corresponds to calculation models of its interior constructed taking into consideration the necessity for satisfying also the value of the dimensionless moment of inertia I we presented earlier.

In its composition, the Earth nucleus, obviously, is close to the composition of iron meteorites and was formed by an iron-nickel alloy called for short "nife" (approximately 89% Fe, 7% Ni, 4% FeS). Up until recent times, a competitive hypothesis about the iron-nickel core was the hypothesis of V. P. Lodochinkov and V. Ramzey according to which the Earth core can be made up of metalized silicates formed as a result of base transitions of silicates to a metal state with pressure on the order of 1 million atm. This hypothesis was not confirmed, however, in the experiments on impact compression with values of parameters corresponding to the physical condition in the core.

The iron-nickel composition of the core corresponds to two more proven hypotheses relative to its formation: by separation from the melt in the process of gravitation differentiation, approximately uniform in composition or due to heterogeneous condensation of solid phases in the protoplanetary cloud. In the first case, the situation reminds one of the well-known process of melting of iron in blast furnaces: the iron reduced to a metallic state settles to the bottom, forming a dense liquid phase and the remaining lighter silicates float to the surface in the form of slag. Another approach developed by A. P. Vinogradov agrees better with ideas about the /207
metal-silicate fractionation of primary matter and the formation of a different class of meteorites. The main argument here is the circumstance that with the beginning of condensation of the protoplanetary cloud from it, in a solid phase, in the first place, a nickel iron is separated (temperature 1460 K) and then magnesium silicates are formed (forsterite, enstatite) and still later different low-temperature condensates (magnetite, troilite, etc.). The metal particles are significantly more easily combined in compact masses than the silicate, forming at first a body of meteorite dimensions. Accumulating,they could be the nucleus for future planets. The portion of high-temperature fraction then must decrease with an increase in distance from the Sun which, in actuality, is observed for planets in the Earth group if one remembers the distribution of their average densities. Subsequent stages of evolution in this page include the process of gravitation differentiation of matter with this difference, that its role is decreased in the initial separation of the material of the core and the shell.

Knowledge of distribution by depth of the velocities of propagation of seismic waves makes it possible to directly determine the course of pressure and density and this means, equalizing the state of matter in the interiors. Two important parameters which determine the thermodynamic shells of the planets -- the Debye temperature and the Gruneisen parameter depend as we have seen on density; these parameters are easier to calculate by using seismic data. Moreover, it appears comparatively simple to calculate a physical model of the inner structure of Earth and the basic thermodynamic coefficients which characterize its structure (heat capacity, coefficient of heat conductivity, compressibility, etc.). Calculation of the actual course of temperature allows, however, noticeable indeterminancies. Experimentally the geothermal gradient with which the heat flux from the core of Earth is directly related is found only for the highest layer comprising on the surface of Earth an average value of 20 k/km with noticeable variations in different regions. But with depths, the increase in temperature slows down. The boundary conditions here are real temperatures of melting the matter -- those mineral associations which we have briefly mentioned when discussing the model in Figure 75. Therefore, distribution of /208
temperatures along the curves of melting have their own type of criteria which determine the position of their lower boundary.

Another criterion is the expression that in the liquid core temperatures must correspond to the adiabatic law. Then the temperature gradient of the main mechanism of heat transfer is convection. The convective state of the Earth's core encompassing, obviously, not only the core but also the mantle, right now essentially is not in question. With the presence of developed convection in the core obviously a large magnetic moment of Earth can be explained as a result of the electromagnetic induction in the moving medium. According to the hypothesis of the hydromagnetic dynamo already mentioned, it is created by movement of the conducting liquid which leads to self-excitation of the magnetic field in a manner similar to how current generates a magnetic field in the dynamo-machine with self-excitation. Temperature in the central part of Earth comprises according to modern hypotheses, about 6,000 K pressure 3.65 Mbar and on the boundary of the core with the low mantle 4300 K and about 1.4 Mbar.

The data on distribution of velocities of seismic waves in the body of the Moon were obtained according to results of an 8-year study of seismographs on its surface which was carried out as part of the automatic complex equipment at the Alsep left in several regions by the Apollo expeditions. For this period, 2775 lunar quakes were recorded with deeply placed foci and a set of other events occurred related to impact of meteorites. From the number of lunar quakes presented, about 80 were identified with sources lying at a depth of 800-1000 km where it is assumed the zone of partially melted rock begins. The noticeable periodicity of deep lunar quakes brought to life a hypothesis about their tidal origins. At this time, the number of events related to the count of a comparatively shallow positioning of sources, for this period, did not exceed 30. These lunar quakes most naturally are related to weak tectonic processes on the Moon which, in turn, obviously are explained by the extremely slow relaxation of stresses caused by compression and extension of its exterior shell.

As to the presence of significant internal stresses of lunar interiors, there is the fact of large irregularity in the shape of our natural satellite, established on the basis of a detailed analysis /209
from the orbit of the artificial Moon satellites. It seemed that the real shape of the Moon, close to spherical equilibrium, deviates from the dynamic which determines a level surface of its gravitational potential (selenoid). Deviation is almost a magnitude larger than on Earth where it is on the order of the square of compression J. With smaller acceleration of the force of gravity than on Earth, this results in shearing stresses comparable to those on Earth which can maintain a lunar lithosphere. Another important result obtained from studies of the gravitational field of the Moon is determination of its dimensionless moment of inertia I = 0.391 which, as we see, is very close to a value corresponding to the moment of inertia of a uniform sphere. This means that density of the Moon is approximately constant, that is, in distinction from Earth there is no large concentration of mass of the center.

The inner structure of the Moon today determined according to the data of seismology (Figure 76) can be compared with a photographic survey of the early stage of evolution of Earth. The most outer layer is a crust whose thickness determined only in the regions of basins comprises 6Ø km. It is very probable that on the broad continental areas of the reverse side of the Moon, the crust is approximately one and one-half times thicker.

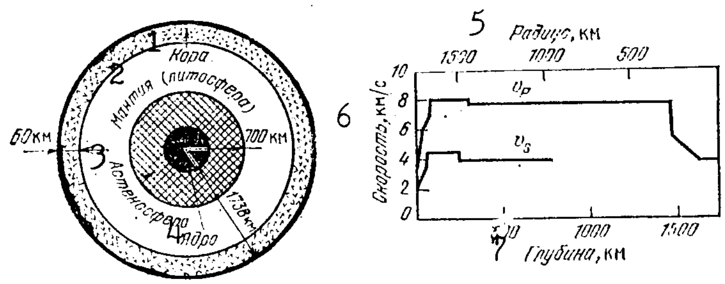


Figure 76. A model of the inner structure of the Moon and the rate of propagation of longitudinal (b_p) and lateral (b_s) seismic waves.
Key: 1. crust; 2. mantle (lithosphere); 3. asthenosphere; 4. core; 5. radius, km; 6. velocity, km/s; 7. depth, km.

The crust is comprised of igneous crystalline rock which is already well known to us -- basalts. However, in their mineralological composition, the basalt of continental and sea regions have noticeable differences. While the more ancient continental regions of the Moon were primarily formed by light rock -- anorthosites, almost entirely composed of average or basic plagioclase, with the small admixtures of pyroxene, olivine, magnetite, titanomagnetite, etc., the crystalline rock of lunar seas, like Earth basalt, is made up basically of /21Ø
plagioclase and multiclinal pyroxenes (argites). They were formed as a result of cooling on a lunar surface or close to it, that is, they are volcanic rocks. At the same time, in comparison with Earth basalts, the lunar basalts are less acid and this means that they were crystallized with a lower ratio of oxygen to metal. In them, moreover, one observes a smaller content of certain volatile elements and at the same time enrichment by many hard-to-melt elements in comparison with Earth rock. Due to admixtures of olivines and particularly ilemenite, the regions of the seas seem to be darker and density of the components of their rock is higher than on the continents.

Under the crust is located a mantle in which, like the Earth, one can separate the upper, middle and lower mantles. The thickness of the upper mantle is about 25Ø km and the middle about 5ØØ km and its boundary where the lower mantle is located at a depth of about 1ØØØ km. Up to this level, the velocity of lateral waves is almost constant and the matter of the interior is found in the solid state which is a thick and relatively cold lithosphere. Due to the large extent of the lithosphere, whose matter is very poor in volatile substances, the Moon has a high Q-factor and therefore the excited seismic oscillations (for example, with incidence of a meteorite on the lunar surface) does not damp for a long time -- we are saying that the Moon "rings like a bell."

The composition of the upper mantle is presumably olivine-pyroxene and at a great depth there is spinel and encountered in the ultra-base alkaline rock, the mineral melilite. On the boundary with the lower mantle, the temperature comes close to the temperature of melting, from which a strong absorption of seismic waves begins. This field is the lunar asthenosphere. At its center, obviously, one finds a small liquid core with radius less than 350 km through which lateral waves do not pass. The core can be iron-sulfide or iron; in this latter case, it must be smaller which agrees better with estimates of distribution of density in depth. Its mass, probably, does not exceed 2% of the mass of the entire Moon.

The Structure and Thermal Evolution of the Planets of the Earth Group

In distinction from Earth and the Moon, for other planets, /211
seismic data are still not available. Therefore, during calculation of models of their inner structure, scientists have encountered tremendously high barriers. The basic difficulties involve the necessity for making equations of state of matter corresponding to the actual change in density with depth more precise as well as specifying the course of temperature responding to the mineralological composition assumed taking into consideration the appropriate curves of melting. Then, the actual realization of processes leading to separation into a silicate shell and heavy dense core and also determination of the nature of the core significantly depend on relative primary contents of elements and the initial chemical and mineralological complexes. The indeterminancy retained here is especially acutely apparent when designing models within whose framework attempts are made to trace the thermal history of Earth and its near neighbors.

According to the present view, differentiation of the component matter begins even at the stage of accumulation a planet of the Earth type or directly after its completion under the effect mainly of the gravitational energy of accretion and the energy of radioactive decay. From other sources of heat, an important role in the initial phase could also have been played by tidal dissipations, separation of heat during adiabatic compression of the inner layers and impact of bodies which form the planet, beam and corpuscular energy of the Sun, Joule heat. The paths of evolution of the Earth planets including the global process of separation into shells was, however, different and depended primarily on the dimensions of the body which determined the significant structure and heat condition of their core. Different aspects of the general problem of the inner structure, chemical and thermal evolution of the Earth, the Moon and planets were considered by Soviet scientist V. Yu. Levin, V. S. Safronov, V. N. Zharkov, Ye. A. Lyubimova, G. V. Voytkevich and many foreign scientists. A detailed analysis of individual questions is contained in the work of these authors and also in the handbook entitled Cosmochemistry of the Moon and planets (see the list of references at the end of the book).

The course of evolution is determined by the balance between the intensity of generation of thermal energy (taking into consideration the heat of melting) and cooling due to convection and heat conductivity. One of the basic sources of energy is radiogenic heat generated by lithophilic elements belonging to the group of long-living isotopes of uranium, thorium and potassium: U-238, U-235, Th-232, K-40. When modeling the thermal evolution of the planet usually they begin with the initial content of these elements corresponding to one or another model of condensation of a protoplanetary nebula. The most precise quantitative criteria are **established for Earth,** the moon and meteorites for which the ratio of hard-to-melt lithophilic elements of uranium and thorium are approximately identical (≈3.5) at the same time that in the relative content of potassium one observes significant differences. The largest ratio of K/U ($\approx 8 \cdot 10^4$) in carbonaceous chondrites (close in their composition, as we have seen, to the average content of elements from the Sun) approximately a magnitude smaller for Earth rock and even half a magnitude smaller for the rock of the Moon. The latter is in good agreement with the general impoverishment of volatile and chalcophilic elements of the lunar matter delivered to Earth by the Luna automated probes and the Apollo expeditions; this matter, in composition, was much closer to an achondrite. /212

At the same time, in it one detects an excess content of uranium and other hard-to-melt lithophilic elements which is an indication of the condensation of matter of the Moon from the high-temperature fraction of the protoplanetary nebula and acutely poses the question of the position of formation of the Moon in the solar system. It is just this circumstance which has brought to life the hypothesis about the initial formation of the Moon within the orbit of Mercury and its transition due to tidal perturbations occurring then from a more distant orbit with subsequent attachment to Earth. Although this scenario is contradicted by the small average density of the Moon, nevertheless, paying attention to the measured value of thermal flux from the lunar interior (taking into consideration its mass), one must assume that in enrichment by radioactive sources of heat, the matter of the Moon exceeds the matter of Earth. Their content appears approximately the same as the content required for a model of thermal evolution of Mercury. As to the other planets, this initial abundance of long-lived radioactive isotopes for Venus is assumed to be close to that for Earth and for Mars -- intermediate between Earth and chondrite. /213

Also, short-lived radioactive isotopes could have played an important role in the earliest stage of evolution of the primary matter of Earth and the planets; these isotopes, primarily isotopes of aluminum Al-26 and also berylium Be-10, iodine I-129, chlorine Cl-36 and certain transurani elements -- plutonium Pu-214, curium Cm-247. Inasmuch as, in Al-26 and the majority of other isotopes, the period of half-decay comprises no more than 1-10 million years, all of these isotopes can be considered extinct. However, they obviously facilitated rapid heating of condensed large meteor bodies and protoplanets, strongly accelerate at the beginning of the process of their chemical differentiation which, moreover, explains the closeness of ages of meteorites which are different in composition. In distinction from isotopes of heavy elements which formed due to processes of nuclear synthesis, the light isotopes (Al-26, Be-10) as was noted, obviously are products of explosion of a supernova star or irradiation of the protoplanetary nebula by intense corpuscular radiation of a young Sun. These isotopes occur in insignificant quantity and at the present time, under the effect of solar corpuscular flux in the material of the surface rock of the Moon and meteorites and also in the atmosphere of Earth.

Generation of radiogenic heat of long-lived isotopes for the entire history of Earth was put together according to an evaluation of Y. A. Lyubimovoy as $0.9 \cdot 10^{38}$ erg at the same time that the total loss is due to thermal flux (contemporary average value $\tilde{\approx}75$ $erg \cdot cm^{-2}s^{-1}$ or $1.79 \cdot 10^{-6}$ $cal \cdot cm^{-2}s^{-1}$) did not exceed $0.54 \cdot 10^{38}$ erg. However, in the process of thermal evolution, the flux could change and therefore we consider that a more real value for total thermal loss due to radiation in space is almost twice as large. Generation of radiogenic heat of short-lived isotopes was more effective, as was noted at the stage of formation of planetesimals and with small dimensions of bodies it would have to have been emitted into the surrounding space. In the planet which was formed, the most intense heat generation, obviously, was due to the release of potential energy in the process of gravitation differentiation of the components matter. In a book by A. S. Monin on the history of the Earth (see references), he presents what seems to us to be a more real estimate of heat generation within Earth along with the energy of the gravitation differentiation for /214
4.6 billion years at about $2.5 \cdot 10^{38}$ erg. Consequently, paying attention to this, the heat losses of approximately $1.8 \cdot 10^{38}$ erg of accumulated heat led to overheating and melting of the Earth interior. Melting was achieved only in the field of the core inasmuch as for full melting at all levels one would have needed twice as large an amount of energy (about $3.2 \cdot 10^{38}$ erg) and consequently, the Earth did not pass through such a stage. From this, one can conclude that the average by mass initial temperature of the Earth's interior did not exceed 1700 K and at the same time, probably, was 300-400 K lower.

Generation of heat had to coincide with heat exchange and cooling. As in the giants, the coefficient of heat conductivity of the exterior shells of the planet of the Earth group is small and therefore equalizing the temperatures in this way occurs very slowly and ineffectively. The main mechanism for heat transfer which determines intensity of cooling of planetary interiors, is convection. With the presence of a convective shift and outflow of heat from the depths, the so-called zonal melt is involved (known in technology also as zonal recrystallization used when refining materials); it was described in detail by A. P. Vinogradov and his coworkers for the matter of chondrites appropriate to differentiation of matter of the Earth's mantle. A mathematical model of the evolution of the zone of melting in the thermal history of Earth was considered by A. N. Tikhonov, Ye. A. Lyubimova and V. K. Vlasov with a certain dependence on time and depth of distribution of thermal sources and coefficients of heat conductivity. Then, the main accomplishment of subsequent multiple (up to 18 times) formations of the zone of melt in the upper mantle with intervals 100-170 million years was pointed out; it agrees well with the time intervals between tectonic-magmatic epochs.

In the light of modern cosmochemical and geophysical data, the hypothesis of the zonal melt has not been shared by many scientists. Moreover, it is clear that inasmuch as for the growth of pressure, the temperature of melting of silicates is particularly sensitive, but not for iron, for their melts there must exist a certain optimum depth most probably in the field of the middle and upper mantle. At this depth, melting of the material of the chondrite composition must begin with drift of light and heavy fractions in opposite directions /215 corresponding to the surface and to the center. In this multistage process which encompasses practically all horizons, the formation of the core is improved and at the same time the lithosphere and asthenosphere of the planet are formed. Inasmuch as the long-lived isotopes of uranium, thorium and potassium belonging to a group of lithophile elements have an affinity for silicates, that is, the capability to substitute atoms in crystal lattices constructed from silicon dioxide SiO_2, during gravitational differentiation they, along with the silicates drift upward. Therefore, they mainly accumulate in the base rock of the crust and with transition to ultrabase, the content of them with less acid in the rocks of the mantle drops sharply. The heat generated by these radioactive isotopes obviously, is diverted by radiation from the surface basically forming the required thermal flux and almost expending no heat in the material found at a large depth. From this it follows that the larger the heat flux, the larger is the degree of differentiation of the interior which occurs.

Horizontal movement of the matter of the mantle at the apices of the large-scale convective cells which form can cause a shift in individual parts of the lithosphere (rigid lithosphere plates) as is proposed for Earth within the framework of the hypotheses of new global tectonics. Let us remember (see page 65 [of the original]) that the boundaries of the lithosphere plates are tectonic breaks in the axial line of seismic lines of Earth and the adjoining plates themselves undergo relative to each other horizontal shifts (displacement, separation and underthrust) as a result of the sub-crust flow in the mantle. The zone of ascending convective flows coincides with the global system of the middle-ocean ridges and the zone of descending flows -- with the system of deep-passing trenches on the periphery of the Pacific Ocean. In the areas of separation where rifts form, the formation of the crust of an ocean type occurs and protrusions of deep ultra-axial mantles of rock are formed. In areas of underthrust adjacent to regions of island arcs, underthrust of one plate under another occurs similar to the formation of hummocks as a result of lateral pressure of the ice fields. In zones of contact of ocean and continental slabs, the rock of the basalt crust along thick layers of sediment accumulated in these regions of the /216 troughs are immersed at great depths in a field of high pressure and temperature where their secondary remelting and metamorphosis occurs.

As a result, basalt and andecite magma formed during remelting increase below the layer of the crust of the continent type. These processes are related to the formation of rock bands on Earth such as the Alpine-Himalaya or Euro-Mountains. The approach of the slabs and collision of dust on these continents resulted in the intense deformation of the Earth's crust, the formation of tectonic cover and folding. As to the Moon, Mercury and Mars, these or other characteristics of the relief of their surfaces are directly related with the processes of global tectonics of slabs hardly possible but in an equal way it is impossible to fully exclude this hypothesis for certain stages of thermal evolution.

As we have already noted, the study of problems of thermal evolution causing a vital interest in scientists, in recent years, is being stimulated by many special features of the "geological chronology imprinting on the surfaces of planets which we have discussed in the preceding chapter. Along with the more specific data on thermal sources based on the study of the matter of the Moon and meteorites, this has resulted in an increase in verification of the calculated models of the inner structure in remote and modern epochs. The existing approach to the problem is fairly completely expressed in an overview by well-known American scientist M. Toksots and D. Johnston in their collection entitled CosmoChemistry of the Moon and Planets.

Figure 77 shows the curves of thermal generation E calculated by these authors for the Moon and planets of the Earth group (with the initial contents of U, Th, K discussed above) per unit of mass of the planets depending on time t. The change in intensity of thermal generation is directly related to the evolutionary stage through which the planet has passed. Their sequence, primarily responding to the earlier precambrian period in the history of Earth is noticeably apparent on the Moon in the chronology of lunar rock. These data make it possible, first of all, to isolate a stage of early volcanism with evacuation on the surface of the light fraction of the melt and the formation of a feldspar crust about 4.6 billion years ago which led to smoothing of residual irregularities in the relief after completion of accretion and a stage of continuous magma activity between 4.4 and 4.0 billion years ago with the formation of anorthosites enriched with /217
aluminum and calcium rock. At this same stage, shell rock was formed -- breccia; partial or complete remelting of the magma rock occurred during incidents of meteorites and metamorphosis of the ancient crust.

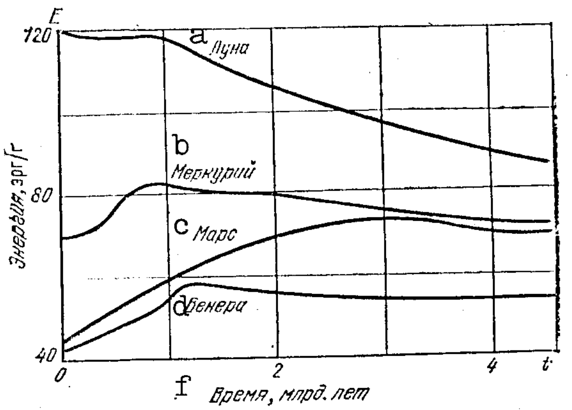


Figure 77. Energy generation related per unit of mass of matter and time to the process of thermal evolution of the Moon and planets of the Earth group.
Key: a. Moon; b. Mercury; c. Mars; d. Venus; e. energy, erg/r; f. time, billion years.

The most intense bombardment of the surface of large meteorite bodies, obviously, relates to the stage of formation of lunar seas about 4.0-3.9 billion years ago. Meteorites broke down the thin crust covering the focus of the basalt melt which resulted in filling of the cavities formed and possibly, their subsequent certain precipitation with the formation of local concentrations of mass -- mascons. Anomalies of the lunar gravitational field are related to them; here, the internal shearing stresses in the lithosphere are particularly large. The asymmetric position of the lunar basins which are the most level sections of the surface can explain the large concentration of the basalt melt on the visible side of the Moon and relatively lighter and thicker crust on the reverse side where bombardment by meteorites resulted only in the formation of deep craters in solid rock. Possibly this is the result of the shift mentioned earlier of its center of /218
mass relative to the center of the geometric figure.

This, obviously, is a more intense period of lunar evolution which answers the maximum generation of energy E(t) for Figure 77 and the magma activity on a large scale. Then distribution changed according to depth of thermal forces due to ejection of the silicate magma enriched with radio isotopes of lithophile elements toward the surface and simultaneously passage of the heavier elements toward the center. The rise in temperature of the mantle and its melting was the result of generation of radiogenic heat and gravitation differentiation of matter. Filling of the lunar seas, in all probability, was completed about three billion years ago. The increase in the youngest crystalline rock among the samples of soil delivered to Earth dated 3.16 billion years ago corresponds to this. The period of melting changed with the rapid cooling and formation of an extensive solid lithosphere whose thickness according to the present evaluation occurred with a rate of about 200-300 km/billion years. Correspondingly, the field of existence of the melt in the mantle was deeper so that the zone of partially melted asthenosphere could be retained at the present time only close to the center (see Figure 76). The basic differences in theoretical models within the structure of the Moon related to the presence of the necessary attempts toward formation on the Moon of a metal nucleus. They depend on the initial assumptions relative to the initial concentration of radioactive isotopes and, consequently, the effectiveness of thermal sources and their uniform or non-uniform distribution by depth and also the role of convection in transfer of heat at an earlier stage of evolution and the degree of hardening of the core as a result of cooling of the lunar interior. The temperature in the core depends on its composition and, obviously, is included within limits 1300-1900 K. The lower boundary corresponds to the hypothesis on enrichment by heavy fraction of protomatter of sulfur, primarily in the form of sulfides and the formation of a nucleus from the eutectics Fe-FeS with melting temperature (hardly depending on pressure) about 1300 K. The hypothesis about enrichment of the protomatter of the Moon with light metals (Mg, Ca, Na, Al) agrees best with the upper boundary; they come in together with silicon and oxygen in a composition of the most /219 important rock-forming minerals of the base and ultrabase rock -- pyroxines and olivines.

The fact of the decrease in content in the Moon of iron and nickel favors this latter hypothesis; the low average density affects its determination. A. P. Vinogradov explained this circumstance that the accretion of the Moon could be depressed by the Earth. Therefore, both these and dozens of other siderophile elements -- the ordinary satellites of metallic iron (along with them, the rock existing in Earth due to closeness in physical and chemical properties) could be lost even at the early stage and with lower temperature accretions on the Moon, more intensely accumulate relatively lighter elements. Nevertheless, within the framework of this hypothesis, one cannot successfully find an explanation of the obvious enrichment mentioned of the lunar matter with hard-to-melt lithophile elements in connection with the fact that the question on the position of formation of the Moon close to and along with the Earth or far from it remains open.

A very small and possibly only partially melted core makes it possible to understand why, in the modern epoch of the Moon, there is not a magnetic field (upper limit of its intensity does not exceed 1 gamma or one hundred thousandth part of an oersted) and correspondingly, why the plasma of the solar wind flowing past it does not undergo excitation. Moreover, the residual magnetization established of lunar rock hardly explains the directed field during impact of meteorites and more likely forces one to assume that either in some period of its history the Moon had a field of internal origin (obviously caused by the mechanism of the hydromagnetic dynamo in the existence of the then melted nucleus), or that the formation of the Moon occurred in the presence of an external magnetic field with intensity at least several thousand gamma. The latter assumes, however, strong limitations on the model of thermal evolution of the Moon, requiring that the temperature in the mantle always remained below a certain critical temperature of phase transition in which a series of physical properties of matter changes (the Curie point) equal to approximately 100 K.

At a temperature higher than the Curie point, matter containing ferromagnetic material loses its magnetic properties. On the basis of the entire set of existing data, English geophysicist S. Rankori looks /220 at the most probable model according to which at the beginning of its history the Moon could have possessed a field with intensity on the order of 1 E but have lost it as a result of cooling and cessation of internal movement after approximately 3.5 billion years.

The existence of a powerful cold lithosphere capable of withstanding the stress created by the mascons in a natural way explains the reason that in the modern epoch, the Moon is tectonically hardly active. The maximum value of released seismic energy (with foci of activity at a depth of 700-1200 km) according to estimates does not exceed 10^{13} erg/year at the same time that on Earth it reaches 10^{25} erg/year which comprises, on the average, $3 \cdot 10^{10}$ W.

Mercury underwent a similar process of evolution obviously and not only the curve E(t) on Figure 77 is evidence of this but also many common characteristics of the lunar and Mercury topography. Here, as we have seen, unique examples are retained of the most ancient structures, slightly changing appearance with subsequent processes. Moreover, the condensation nature of the primary matter of Mercury is different, basically showing comparatively high-temperature fractions of iron meteorites. Actually, this average density is significantly higher than the lunar and somewhat exceeds the average density of Earth. The latter, however, is explained by the fact that the matter of the Earth interior is found with significantly larger pressure due to the difference in mass of the planets. Consequently, for reaching almost the same average density of Mercury, a relatively large quantity of heavy elements must be maintained; taking into consideration the cosmic propagation, the most important of these must be iron. According to the data of the well-known American geochemist G. Urey, the ratio of Fe/Si for Mercury is approximately twice as large as for Earth and five times as large as for Mars. It was already mentioned above that the explanation of this sharp decrease in content of iron with an increase in the heliocentric distance fully falls within the framework of the condensation model of protoplanetary matter with the presence of metal-silicate fractionation.

As a result of the decreased content of silicates, there is a hypothesis that in the initial matter in orbit of Mercury there was considerably less of the radioactive elements in comparison with /221
matter of chondrite meteorites (according to an estimate 2.5 times). In this case, within the framework of the simplest uniform models with a ratio Fe/Si ≈1.4 calculated by S. V. Kozlovskiy, it was not possible to obtain a temperature of the interior of Mercury higher than 2300°K for all stages of evolution which is below the temperature of the solidus (and of the equilibrium of crystallization) in the Fe-Si system. This is inadequate for separation to a shell with generation of a heavy nucleus and formation of a crust. In later models, however, attention was given to the fact that at the stage of condensation of the primary matter, before generation from gas of the metallic iron, Mercury, like the Moon, could maintain hard-to-melt lithophile elements and retain then the enrichment by uranium and thorium and with a very small content of potassium and other volatile elements. Using this assumption, R. Siegfried and S. Solomon showed that Mercury could be differentiated and form a nucleus. The process of differentiation occurred, obviously, very early, soon after the completion of the basic phase of accretion which is evidenced by

traces of early volcanism on the Mercury surface. As in the models calculated earlier, it was assumed that with further thermal evolution of the planet high conductivity of the iron was important comprising about 70% of its mass. Then it was found that the core of Mercury had to have hardened approximately 2 billion years ago if one did not assume retention in it of thermal sources right up to the present time.

Some scientists have named the continuing decay of potassium as such a source which simultaneously provides a more rapid formation of an iron core and melting of the mantle. Calculations showed that for retaining the core in a partially melted state, the present content of potassium had to be insignificant, several magnitudes smaller than matter of the lunar soil. Drift toward the surface due to processes of shift could be ineffective in redistribution of potassium and more than this practically not right now in the Mercury crust. In particular, this is evidenced by the very low threshold for the content in the atmosphere of Mercury of the argon isotope Ar-40 which is a product of beta-decay of K-40 in the crust of the planet established according to the data of measurement using the ultraviolet spectrometer on the Mariner 10 spacecraft. This threshold proved to be significantly lower than the measured content of argon on the Moon where it is absorbed into the soil with low soil temperatures and with the rise of the Sun, its partial pressure increases by approximately a /222
magnitude. Such an accumulation of argon, obviously, does not occur on Mercury, which is a serious limitation when evaluating the content of potassium in the crust but does not contradict the idea of maintaining it in the interior.

With conditions of retention in the nucleus of this or other hypothetical thermal sources, one can understand the presence on Mercury of a significant magnetic field, starting with the concept of its generation due to the hydromagnetic dynamo. The hypothesis of residual magnetization is considerably less probable inasmuch as for Mercury it is even more difficult than for the Moon to assume that the temperature in its interior did not rise higher than the Curie point. The magnetic field was recorded by N. Ness and his coworkers with flight around the planet by the Mariner 10. The intensity of the basic dipole component of the field at the surface on the equator comprises 350 gamma, or ≈1% of the Earth's; the axis of the magnetic dipole is formed with the axis of the orbit an angle of 12°. Plasma measurements close to Mercury confirm that the field belongs to the planet itself and is not induced with the flow of solar wind: the structure of the limited field of space--the magnetosphere and a number of specific features of streamline flow of the planet with intrinsic regular field are evidence of this. This includes the presence of a magnetopause, an impact wave (formed at a distance of ≈1500 km from this surface at the same time as during interaction with a very rarefied atmosphere it would be approximately a magnitude closer) and a number of effects, which, similarly to Earth, obviously, are caused by processes of acceleration of captured particles in the field of the magnetic loop.

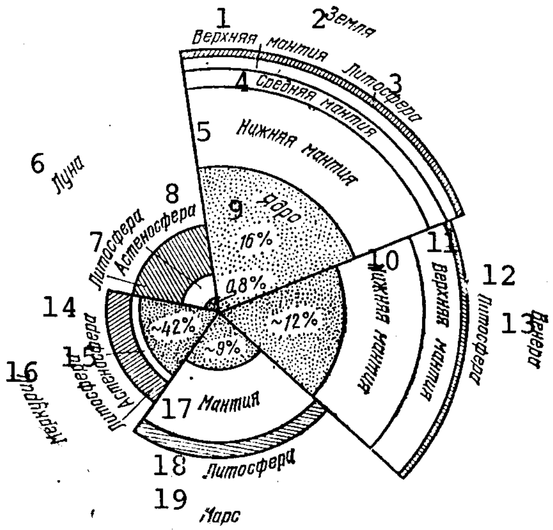


Figure 78. A comparison of models of the inner structure of planets of the Earth group. Relative dimensions of the core are indicated in volumetric percent.
Key: 1. upper mantle; 2. Earth; 3. lithosphere; 4. middle mantle; 5. lower mantle; 6. Moon; 7. lithosphere; 8. asthenosphere; 9. core; 10. lower mantle; 11. upper mantle; 12. lithosphere; 13. Venus; 14. asthenosphere; 15. lithosphere; 16. Mercury; 17. mantle; 18. lithosphere; 19. Mars.

Thus, independent of the thermal model used, one can confirm that Mercury, like the Moon (although somewhat later) reached the apex of evolution in the early stage of its history and at the present time continues to cool. As is apparent from Figure 78, in which a model is shown of the basic shells of the planet, the iron-nickel core of Mercury comprises about 3/4 of its diameter, that is, it is approximately equal to the dimensions of the Moon and /223 most of all is partially melted. It is surrounded by a thin mantle, probably, consisting of magnesium silicate rock of the olivine type and along with the upper crust layer a solid lithosphere of Mercury is formed. Its thickness increased from ≈200 km about 3 billion years ago to ≈500 km at the present time. The fairly large intensity of the lithosphere gives us the basis for assuming a low level of modern tectonic activity. It is possible, however, to assume that as a result of the longer period of cooling, the processes of global tectonics and ancient volcanism encompassed a larger period of Mercury history than lunar. From this it follows that the age of the youngest rock on the plain sections of the planet inside the craters and basins subjected to filling by igneous lava must be noticeablyless than the minimum age of 3.16 billion years determined for the rock of the Moon.

The special features of morphology of the relief presented already for the escarpments discussed earlier in a system of extensive steep outcroppings with toothed outlines makes it possible to consider Mercury a planet on which tectonic processes have a unique character. They were caused by its general global compression and showed, obviously, the direct result of formation of a large core after /224 approximately 1.2 -1.5 billion years after accumulation of the planet, followed by a long period of cooling. The cooling and compression began soon after completion of the period of intense bombardment of the surface by large meteorites and continued after formation of broad, flat ravines and basins hindering moreover the appearance of surface volcanism. It is possible that in the initial stage of this process tectonic cracks occurred; however, the formation of folded structures encompassing the entire latter period of thermal evolution of Mercury were dominant. They are more characteristic for this planet, in spite of the traces of the extent of the crust of tectonic origin on the Moon and Mars which have a more average density.

The evolution of Venus, obviously, in its characteristics, is similar to that of the Earth and also is characterized by comparatively early differentiation of its interior. Models of the inner structure are calculated, starting from a composition of protomatter in orbit of Venus close to Earth with somewhat fewer admixtures of volatile elements. Correspondingly, one obtains on the whole a structure similar to that of Earth for the interior of this planet. The radius of liquid iron of the core is estimated, approximately like that on Earth, equal to 2900 km if one assumes that the dimensionless moment of inertia I of Venus is equivalent to that of Earth. The model in Figure 78 also assumes, similarly to Earth, the existence of a lithosphere, thickness about 100 km, upper and lower mantles. Their mineralological composition, obviously, differs little from the composition of the components of the rock in the shells of Earth. This confirmation is not contradicted by data obtained earlier for determining the composition of soil in the landing areas of the Venera station which discovered rock of basalt type in the crust close to toleite and potassium alkali basalt. The results of these measurements are also evidence that on Venus, as a result of gravitational differentiation of matter, evacuation occurred in the crust of long-lived isotopes. The calculated value of the thermal flux from its interior comprises about 100 erg/cm^2·s; approximately such values were recorded on Earth in the fields of modern volcanism.

[Pages 225-256 were not included for translation.]

The existence of carbohydrates led to hypotheses about the possible abiogenic organic synthesis in the atmosphere of Jupiter under the effect of solar ultraviolet and high-energy corpuscular radiation, and also thunder and lightning in clouds occurring thanks to effective separation of charges in high convection conditions. C. Sagan and B. Kkhar conducted experiments on modeling such a type of process, making it possible to obtain a broad class of complex organic compounds right up to amino acids and to identify their spectral characteristics in the visible and near infrared areas of wavelengths with the spectra of Jupiter. It is possible that organic polymers which have a broad range of colors make a certain contribution to the coloration of Jupiter. However, here obviously, the basic role is played here by the amorphous red phosphorus during separation of phosphate, the hydrogen and ammonia polysulfides and sulfur. They color the disk of the planet reddish brown and yellow inasmuch as their basic components are hydrogen and helium and also methane and ammonia in any phase, remain practically colorless.

The model of the upper part of the Jupiter gas cloud shown in Figure 80 [Figure 80 was not included for translation] is constructed according to the data of measurements of temperature using infrared radiometers and radio-eclipse measurements during flights around Jupiter by the Pioneer and Voyager spacecraft. The zero altitude corresponds to a certain randomly selected value on the pressure scale. A pressure of 1 atm corresponds to a temperature of 170 K. The tropopause is found at a level with pressure 0.1 atm and temperature 115 K. In the entire troposphere lying below, the altitude course of temperature can be characterized by the adiabatic gradient in the hydrogen-helium atmosphere -- about 2 K per kilometer. The spectrum of Jupiter's radio emission also is evidence of a stable increase in radio brightness temperature with depth. Above the tropopause is located the field of temperature inversions where the tempera- /258
ture right up to a pressure on the order of 1 mbar gradually increases to $\approx$180 K. This value is retained in the mezosphere which is characterized by isothermia to a level with pressure approximately 10^{-6} atm and above that begins the thermosphere changing to the exosphere at a temperature of 1250 K.

Figure 80 also shows the proposed structure of clouds of Jupiter. According to this model, there are three basic layers: the upper layer at a pressure of about 0.5 atm consisting of crystal ammonia; an intermediate layer comprising hydrosulfide of ammonia; the lowest layer -- with pressure of several atmospheres comprising an ordinary water ice. This model on the whole satisfies the set of existing experimental data and explains well the characteristic coloration of zones and bands: the light zones located above in the atmosphere contained bright white crystals of ammonia and the bands located more deeply -- the red-brown crystals of ammonium hydrosulfide. In certain models, starting with the geochemical expressions, it is also possible to assume the existence of an even lower fourth layer of clouds consisting of liquid ammonia. Similarly to Earth and Venus, lightning has been recorded in the atmosphere of Jupiter. Judging from the light flashes seen on the photographs from the Voyager, the intensity of charges is extremely great. However, it is still unclear to what degree these phenomena are related to the clouds inasmuch as the flares are detected at higher altitudes than one would expect.

The effective temperature of Saturn, as the result of the great distance from the Sun, is lower than on Jupiter. But as a whole, the structure of the atmosphere, the profiles of temperature and pressure, the density of the cloud cover are similar to the Jovian although the surface of the clouds appears more uniform than possibly is explained by the presence of an extensive super-cloud smoke (see Figures 65 and 66). According to the data of radio measurements on the Voyager 2, temperature at the level of pressure of 1.2 atm comprises about 145 K and slowly decreases with the adiabatic gradient 0.85 K/km. In the tropopause at a pressure of about 0.07 atm, the temperature is approximately 80 K. The upper boundary of the clouds at the equator, obviously, is located higher than at the poles and their color changes from blue-green in the near-polar zone to red-brown, beginning with a latitude of $\approx 59^{\circ}$ as is seen on the color synthesized images transmitted by the equipment of the Voyager (with certain /259 amplification of color contrast). In the middle and lower latitudes, separate bands and zones are clearly differentiated however more weakly expressed than on Jupiter (see Figure 89 and Figure 94). The zones, obviously, are located above the bands inasmuch as, as measurements have shown using an infrared radiometer, their temperature is lower.

In the study of atmospheres and clouds of Jupiter and Saturn, the results of ground photometric, spectral and polarized observations make a great contribution; these are regularly made by groups of Soviet astronomers direct by V. G. Teyfel, V. P. Dzhapiashvili, A. V. Morozhenko and several groups of foreign scientists. These observations make it possible to study the vertical structure of clouds, trace their spatial-time variations related to dynamic processes in the atmosphere. The interpretation of the spatial features of reflective properties of these planets have made it possible, in particular, to draw conclusions about the aerosol smoke located above the main cloud cover and having greatest optical thickness over the polar regions. Obviously, the darkening of the polar regions is related to its presence, particularly strong in the ultraviolet. However, it is impossible to exclude the fact that a decrease in reflection in the ultraviolet field of the spectrum is due to the existence above the layer of smoke of absorbing particles similar to those which occur in the super-cloud atmosphere of Venus. However, according to measurements on spacecraft, no absorbing agent was detected. During flight around Saturn, intense ultraviolet illumination was recorded due to scattering of atomic hydrogen whose source possibly can be the rings.

The special features of the atmosphere of Uranus and Neptune are explained by the even lower effective temperatures and the large concentrations of methane and ammonia which have already been mentioned. Methane plays a particularly significant role. The spectra of reflection of these planets in the visible field with well-known methane bands of absorption have hardly any differences.

Unfortunately, an analysis of the content of this gas and an estimate of pressure and temperature at the level of formation of the bands is extremely complicated by difficulties in determining the equivalent widths of the lines and the limitation of laboratory data on the CH_4 bands in a spectral interval shorter than 1.1 μm where absorption has a complex character. Therefore, as a standard of comparison usually /260 one uses measurements of equivalent widths in the spectra of Jupiter and Saturn where the content of methane is determined more reliably with an error of no more than ≈50%. According to these results, at the level of formation of bands at temperature ≈90 K on which the CH_4 lines still remain unsaturated, the ratio of the CH_4/H_2 mixture essentially exceeds the solar value and enrichment with carbon reaches approximately 50 times.

The structure of the atmospheres of Uranus and Neptune, obviously, also differ noticeably from Jupiter and Saturn. In particular, their spectra of radio emission are noted here in which the significant increase in brightness temperature is not detected in fields from 3 to 10 cm as is observed with the rapid increase in temperature from the depth. According to the set of results of analysis of spectral observations and calculations of weakening according to altitude of the thermal flux made by R. Danielson, models of the atmospheres of these planets were calculated. Then, different hypotheses relative to the positioning of the effective level of reflection of solar radiation and the boundaries of the cloud layer were used here and the behavior of thermodynamic parameters were controlled by the course of the curve of pressure of saturation of methane vapors. The measured course of brightness temperature closest to reality was explained to be models in which it was permissible to have the thermal flux variable according to altitude and the presence in the atmosphere of inversion layers. However, we still must expend considerable effort so that information on the atmospheres of Uranus and Neptune will be much more definite. Obviously, here a decisive role is played by the planned flyby close to Uranus of the Voyager 2 in 1986.

According to a number of similar characteristics in the spectra of reflection recorded on Earth for Uranus and Neptune, the largest seems to belong to Saturn's satellite -- Titan. Recently, its atmosphere discovered at the beginning of this century by Spanish astronomer K. Sola has attracted a great deal of attention. In the 1940's, the well-known American astronomer D. Koyper confirmed the presence of atmosphere on Titan having detected bands of absorption of methane in its spectrum and later reporting on identification of weak quadripolar lines of molecular hydrogen. But such lines occur due to deformation of molecules with collisions creating their asymmetry and /261 dipolar moment which explains the non-resonant (induced) absorption proportional to the square of gas pressure. This led to a hypothesis about the presence on Titan of a fairly dense gaseous cloud.

The results of studying the dependence of the infrared brightness temperature on wavelength were first interpreted in such a way that a wavelength of 2030 μm corresponding to the expected equilibrium of temperature of Titan (about 90 K) emits considerably less energy than one finds from the Sun and a maximum of radiation is mixed in the more shortwave part of the spectrum. This phenomenon can also be explained if again one allows that Titan has a dense atmosphere in which the basic non-transparency is created in a range of wavelengths about 20 μm. Then the temperature measured on these wavelengths will apply to the emitted layer located at a certain altitude in the atmosphere and temperature on the surface as a result of the greenhouse effect can reach almost 200 K. In other words, the climatic conditions on Titan can be looked at as comparatively favorable, almost the same as those on Mars!

For a long time, the question of which agent can be responsible for this lack of transparency in the atmosphere has been discussed. Methane does not have strong bands of absorption in areas longer than 7.7 μm. As to molecular hydrogen, its required quantity here must correspond to pressure on the surface of at least 0.5 atm and hardly the body of such mass as Titan could maintain so much hydrogen and its constant intense supply into the atmosphere is hardly probable. More exemplary seems to be the hypothesis that the outgoing radiation is screened due to induced absorption of molecular hydrogen at a pressure on the order of 1 atm. Such a high pressure can be created, for example, by neon or nitrogen with relatively small content of hydrogen. The cosmically propagated neon can be retained from the stage of accumulation and the nitrogen be formed due to photolysis of ammonia.

However, the reality of this hypothesis was greatly reduced after doubt was cast on the actual detection of hydrogen in the spectra of Titan. Therefore, two models have been continued to be looked at: non-dense atmosphere with pressure on the surface ≈20 mbar and dense atmosphere with pressure on the surface about 1 atm. The main /262 atmospheric component was considered to be methane. Moreover, basically no exemplary explanation for the possible increase in temperature of the lower atmosphere has been found.

Starting with concepts of the possible formation of hydrocarbons under the effect of ultraviolet radiation on the surface or in the layer of clouds, attempts have been undertaken to explain the nature of the reddish coloration of Titan: its albedo in the red part of the spectrum is as great as that of Mars or Io and, generally speaking, can be caused by the surface or the atmosphere. The presence in the spectrum of fairly blurred, difficult-to-distinguish marks of absorption existing, differently from gases, reflected from solid bodies would appear not to exclude such a possibility. However, a number of special features in the structure of bands of methane and the results of measurements of the dependence of the degree of polarization of the reflected radiation on the phase angle definitely is evidence that like Jupiter and Saturn, the reflecting material was most probably an aerosol concentrated in the clouds.

The results of optical and radio measurements of the parameters of the atmosphere of Titan with flight of the Voyager 1 basically clarified all of these questions. It appeared that Titan actually has a very dense atmosphere with pressure on the surface ≈1.6 atm and temperature 94±2 K, that is, no greenhouse effect is detected. Ninety percent of the atmosphere consists of nitrogen and, probably, also contains up to 10% primary argon and the relative content of methane in all is about 1%; also there is a certain amount of ammonia, hydrogen cyanide, ethane, ethylene and acetylene. Bands of the latter formed in the zone of super-cloud smoke at T≈150 K, and not radiation of the near-surface atmosphere cause an increased brightness at wavelength 8-10 μm.

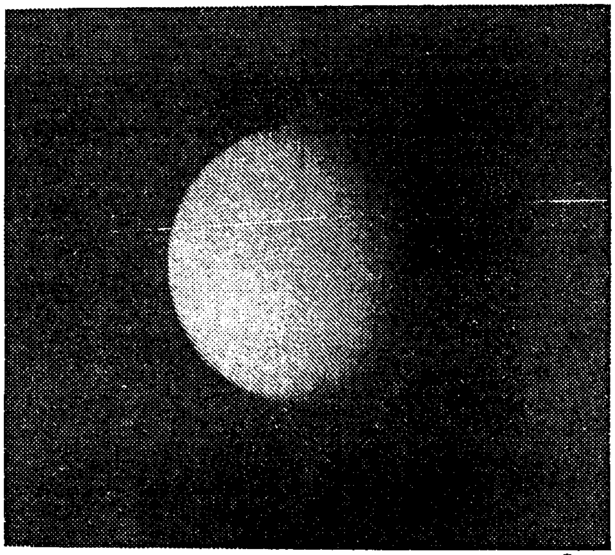


Figure 82. Titan from a distance of 4.5 million km. On the color image close to the actual, the orange color of this largest satellite of Saturn is caused by the super-cloud aerosol layer and the smoke (photograph from the Voyager 1).

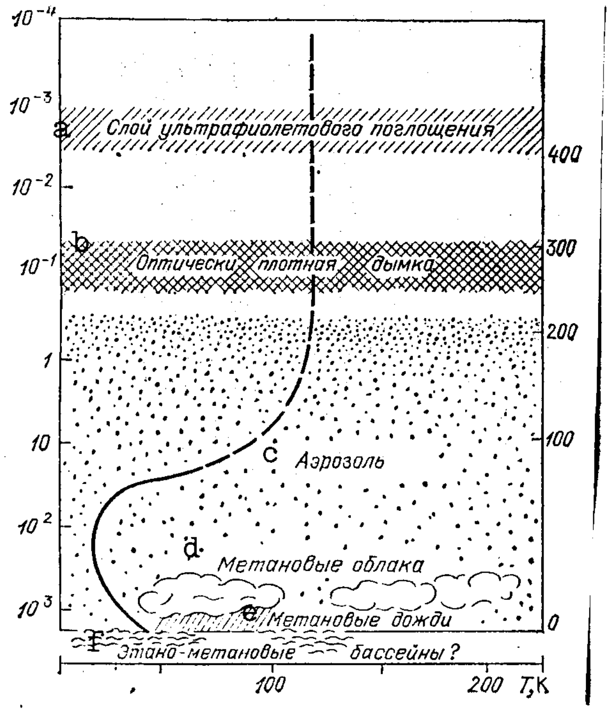


Figure 83. A model of the atmosphere of Titan according to measurement data from the Voyager 1 and Voyager 2. Along the axis on the left is pressure in mbar, on the right -- altitude in km.
Key: a. layer of ultraviolet absorption; b. optically dense smoke; c. aerosol; d. methane clouds; e. methane rain; f. ethane-methane basins?

Clouds and aerosol smoke of the dense shroud which covers Titan does not permit us to see its surface (Figure 82). The clouds consist almost entirely of droplets of liquid methane. It is interesting that with comparable values of surface pressure, the atmosphere of Titan is almost ten times more massive than that of Earth, which is explained by the difference in acceleration of the force of gravity on these bodies.

The basic features of the atmosphere of Titan which correspond to our modern concepts are illustrated by the model shown in Figure 83 /263 where the scale of altitude (on the right) is related to pressure (on the left). Methane clouds are located comparatively low over the surface at the same time that the super-cloud aerosol, obviously, is extended to an altitude of more than 200 km. A dense smoke was detected even higher which is not transparent for the visible range of the spectrum and over it one finds a layer of intense absorption in the ultraviolet field of the spectrum. Only these very upper fields of the atmosphere of Titan can be successfully seen on images transmitted from the Voyager 1 (Figure 84). These data about temperature and pressure of the atmosphere on the surface in the troposphere and stratosphere (solid curve in Figure 83) were obtained by a method which is already familiar of radioscopy where the spacecraft is found on the Titan-Earth line first during setting behind the disk of Titan and then repeated with the rise from behind it.

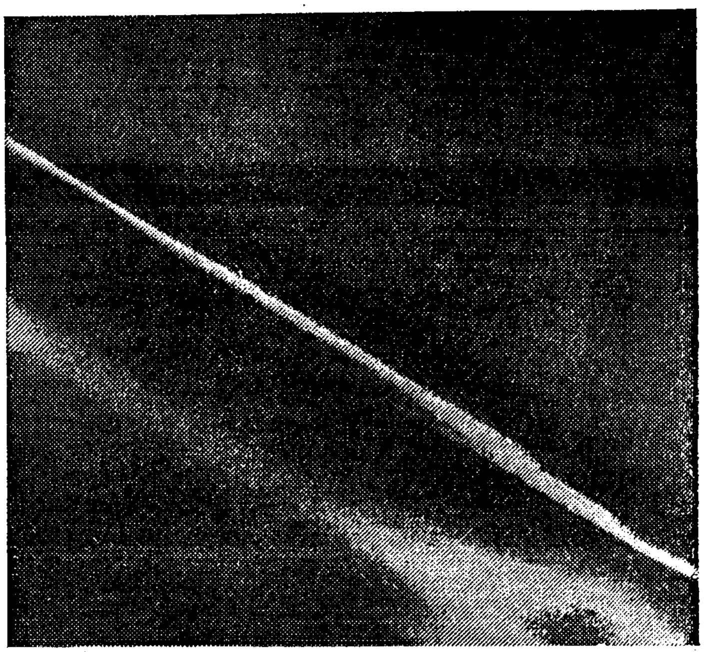


Figure 84. Super-cloud smoke in the atmosphere of Titan on a Voyager 1 photograph makes it possible to see the spectra of individual layers located at altitudes from 200-500 km over the surface. The image is obtained from a distance of 22,000 km.

A dense nitrogen atmosphere to some degree brings Titan and Earth closer together. But the similarity, possibly, is not limited to this. Hypotheses have been put forward that methane could have played the same role on Titan as water has on Earth: found on the surface in a liquid state, it, evaporating and condensing in the atmosphere, forms clouds from which again it falls to the surface in the form of methane rain. Such a cycle of methane could affect in a definite way the meteorology of this heavenly body which is unique in many ways. /264

However, doubt was cast on the accuracy of such an interesting hypothesis by the analysis of altitude profiles of temperature which were measured because there was no noticeable deviation from the dry-adiabatic gradient in the sub-cloud atmosphere detected. Correspondingly, the hypothesis about a methane ocean covering the surface of Titan was brought under dispute although at the values of temperature and pressure shown above, the methane had to be found on the surface in a liquid state. Solving such a controversy can be done if one pays attention to the fact that as a result of the photochemical process in the atmosphere, the methane easily is /265

converted to ethane and also remains liquid with the conditions existing on its surface. A hypothesis about the ethane ocean put forward by J. Lyunay with coworkers and independently by S. Dermott and C. Sagan appears to be fairly attractive. Other atmospheric components could be dissolved in this ocean primarily nitrogen and methane (proposed composition: 70% ethane, 25% methane and 5% nitrogen) and heavier organic compounds could accumulate in the form of precipitants on its bottom, primarily those formed in the atmosphere. Several scientists tend to consider them "frozen" analogs of primary organic complexes on Earth. This hypothesis is considerably better founded in comparison with the contents mentioned about a /266
"thick organic mass" on its surface. Nevertheless, only a direct experiment makes it possible to obtain a final answer, and it is not by chance that Titan is considered now as one of the most attractive objects for future space research.

There is still very little data to answer questions about what kind of an atmosphere Pluto has. The spectral and spectrophotometric measurements did not show traces of absorption of methane in a gaseous phase (which could be found in the form of saturated vapors in equilibrium with surface ice) or any other kind of atmospheric components. A natural way to explain this would be an extremely low temperature on the surface of Pluto which is below the temperature of condensation of the majority of gases. A natural gas which could be maintained on Pluto and not undergo condensation is neon. However, such a hypothesis is hardly probable inasmuch as it has a small atomic mass and cannot be maintained on a celestial body with such a small mass. A similar situation, obviously is characteristic for one more relatively large body on the periphery of the solar system -- the satellite of Neptune, Triton. As on Pluto, here noticeable traces of atmosphere are not detected which could be explained primarily due to freezing of gases which, in conditions of weak insolation in the absence of interior sources of heat, become definite.

In the family of Galilean satellites, the main mechanism which controls the presence of the atmosphere at higher temperatures on the surface is dissipation (velocity) of atoms and molecules in space. Experimentally, by ground observations and according to measurements from the Pioneer spacecraft, the atmosphere on Io was detected with a pressure on the surface of about 10^{-5} mbar and the existence of a toroidal cloud of plasma along its orbit. Taking into consideration the intensive dissipation for maintaining even such a rarefied atmosphere would require a constant output of gases whose source can become clear only after the discovery on Io of active volcanism. In the ultraviolet spectra of the plasma toroid of this satellite, ions of sulfur and oxygen were identified which does not cast any doubt on their volcanic origin. Over individual thermal regions of the surface identified with the foci of volcanic activity, a less rarefied /267
atmosphere was detected consisting of sulfur dioxide (SO_2). On the adjacent cold sections of the surface, the content of SO_2 rarely occurs, that is, it freezes on the surface and the atmosphere collapses, becoming an exosphere.

There are no similar sources for intake of gases into the atmosphere on other bodies of this family. Therefore, only on the largest, Ganymede, has the existence of an ancient atmosphere with pressure on the surface even higher than on Io been proposed. However, measurements from the Voyager showed that pressure does not exceed 10^{-8} mbar, that is, this satellite of Jupiter has almost no atmosphere. The absence of detected atmospheres on bodies which are almost identical in dimensions such as Pluto, Triton, Europa and moreover on Ganymede or Callisto at the same time that the presence of an atmosphere on Titan is apparent is one of the curious phenomena in the solar system which is waiting for an explanation.

On the Boundary of the Atmosphere in Space

Each of the heavenly bodies within the limits of the solar system exist not in isolation but is subject to the effect of processes occurring on the Sun. The change in solar activity is accompanied by significant variations in the flows of electromagnetic and corpuscular radiation which directly interact primarily with the most outer regions of Space adjacent to the planet -- its upper atmosphere, the ionosphere, the magnetosphere. The gaseous and magnetic "shields" of the planet prevent direct penetration to the surface of the more rigid part of the solar spectrum (ultraviolet and X-ray radiation) and the most energetic charged particles present in fluxes of solar plasma. "Having an impact on itself," the region of the near-planetary space undergoes serious changes -- the molecules break down into atoms (dissociate), part of the atoms and molecules ionize and form the ionosphere, part of the power lines of the magnetic field of the planet "are carried away" on the nocturnal side, forming its "magnetic loop." In the magnetic field, processes of acceleration and focusing of particles of solar plasma occur which, invading the atmosphere, cause grandiose natural phenomena -- the aurora borealis. Particles trapped on the power liens of the magnetic field form radiation bands. /268
In the absence of a field, other effects occur whose main role is played by the ionosphere (its profile is indicated in Figure 80).

We have already mentioned the basic parameters which characterize the structure of the atmospheres of Earth, Venus, Mars and Jupiter at high altitudes. In distinction from the upper atmosphere of Earth where a definite role is played by oxygen, the processes which occur in the upper atmospheres of Venus and Mars are basically controlled by photochemistry of carbon dioxide whose predominant content is retained approximately up to 150-200 km along with products of its dissociation O and CO. Higher than this level, the atmospheres of these planets, like Earth, gradually become helium-hydrogen. The hydrogen and its compounds with carbon and nitrogen determine the processes of transfer of solar short wave radiation to the upper atmospheres of the planet-giants.

Intense de-excitation of energy in the infrared bands of carbon dioxide in the upper atmospheres of Venus and Mars, obviously are explained by average exospheric temperatures significantly lower in comparison with that of Earth. The temperature above this field of the upper atmosphere (thermosphere) is called this where the basic influx of energy occurs due to direct absorption by atmospheric molecules and atoms of solar ultraviolet and X-ray radiation and the profile of temperature becomes almost isothermal. The exosphere of Earth begins with altitudes of about 400-500 km from which particles which hardly undergo large collisions can without obstacle escape into outer space. Depending on the time of day and state of solar activity, the exospheric temperature changes on the average from 500-700 to 1000-1200 K. As to Mars and Venus, their exospheric temperatures do not exceed 200-350 K and the basis of the exosphere lies approximately at 200 km lower. Then, in the thermosphere of Venus, the temperature at night, as we have already said, drops to 100 K -- 80 K below the temperature of the mesopause, usually the coldest region in a planetary atmosphere. As Soviet scientist V. F. Gordiets and Yu. N. Kulikov have shown, the reason for this phenomenon can be in addition to the CO_2, de-excitation of energy in the rotational band of water vapor in the infrared region of the spectrum.

Measurements according to method of radio illumination from the spacecraft showed that Venus and Mars have ionospheres; however, they /269
are less dense than those of Earth and are closely pressed to the planet. In the ionosphere of Earth, the maximum electron concentration (up to 10^6 el/cm^3) is observed at an altitude of about 280 km in the daytime -- this is the so-called F_2 layer. Less clearly pronounced maximums lie at altitudes of 150-200 km (F_1 layer), about 110 km (E layer) and 80 km (D layer) where the concentration of electrons is from 10^5 el/cm^3 in the F_1 layer up to 10^3 el/cm^3 in the D layer.

At night, the density of each of these layers is considerably lower. The main ion in the F_2 region is atomic oxygen and molecular ions of oxygen, nitrogen and nitrous oxide participate in ionization of the remaining fields; their role becomes determining for the formation of the D and E layers. Above the F_2 layer, the ion and electron concentration (the ionosphere is quasineutral!) gradually drop and approximately at an altitude of 1000 km are equalized with the concentration of neutral gas (basically hydrogen). At the same time, in all of the underlying atmosphere, the neutral components are dominant; for example, at the altitude of the F_2, the relative content of ions does not exceed tenths of a percent. The most important difference in the ionosphere of Mars from the ionosphere of Earth is the absence in it of a maximum F_2 formed in the Earth's ionosphere due to ions O^+ with certain relationships of the processes of ionization, recombination and diffusion. The cause for this difference is the circumstance that the rate of reaction of recharging of ions O^+ with CO_2 is considerably greater than with N_2 which retains the role of the basic components of the atmosphere of Earth up to comparatively high altitudes. This prevents an accumulation of the O^+ ions on Mars below approximately 200 km.

The basic maximum of the daytime layer of the Martian ionosphere lies at an altitude of 135-140 km and has an electron concentration of no more than $2 \cdot 10^5$ el/cm^3, that is, almost a magnitude smaller than the concentration in the F_2 layer of the ionosphere of Earth. The second maximum is detected at an altitude of about 110 km with electron concentration $7 \cdot 10^4$ el/cm^3. The basic component of the Martian ionosphere is the O^+_2 which forms as a result of reaction of overcharging of the ion with carbon dioxide and atomic oxygen. The ionosphere of Venus also is formed basically by ions O^+_2 with admixtures O^+ and others; above 200 km, ions O^+ predominate. Its daytime maximum with concentrations $(3\text{-}5) \cdot 10^5$ el/cm^3 is located at an /270 altitude of 140 km; the sharp drop in electron concentration is observed at a level of 250-400 km: here one finds the ionopause -- the boundary between the thermal ions of the ionosphere and flows of high-energy particles of solar plasma. On the nocturnal side, an extensive zone is formed up to an altitude above 3000 km with the average concentration of electrons less than 10^3 el/cm^3 and several local maximums at altitudes below 150 km where concentrations are 5-10 times higher and the basic ion is O^+. The composition and content of ions in the ionospheres of Venus and Mars undergo significant variations.

A powerful ionosphere whose extent reaches no less than 3000 km is observed on Jupiter although the maximum electron concentration in it does not exceed $5 \cdot 10^5$ el/cm^3. According to the data of measurement on the Voyagers in the morning and evening conditions and with shifts from the equator to 67^o in latitude, the maximum electron concentration and position of the main peak changed, respectively, from $2 \cdot 10^4$ el/cm^3 to 5 el/cm^3 and from 700 to 2500 km in altitude counting from the apex of the clouds. A much weaker ionosphere was observed on Saturn with a peak of electron concentration $9 \cdot 10^3$ el/cm^3 at an altitude of 2800 km counting from the level with pressure ≈ 1 atm as measurements indicated in the method of radio illumination from the Pioneer 11. Measurements close to this value (from 0.6 to $1.7 \cdot 10^4$ el/cm^3) were found by a similar method in the morning and post-midday hours during the flight of the Voyager 2.

It is interesting that ionospheres were also detected on two of the planet's satellites -- the Moon and Io. The weak ionosphere on the Moon (less than 10^3 el/cm^3) almost adjoins the surface and obviously, is created basically by ions of argon. Io, in the emission ultraviolet spectrum, shows lines identical for ions of sodium and sulfur. These ions, most probably, are formed under the effect of impact ionization of atoms by electrons in the powerful radiation bands of Jupiter.

The problems of physics of the upper atmosphere (planetary aeronomy) are related in the closest manner to the characteristic features of interaction of a heavenly body with accumulating flows of solar plasma. In our ordering of several models, nature allowed a basic difference which consists primarily of the presence or absence in the planets of their own magnetic fields and gaseous shell. As we have seen, among the planets of the Earth group, only Earth has a significant magnetic field and the other maximum cases the Moon devoid /271 both of a magnetic field and an atmosphere. In turn, the strong magnetic field of Jupiter which exists, in a number of special features, is similar to a pulsar -- the source of pulsing radio emission and in it a commonality of physical mechanisms acting in the universe is apparent.

We do not have the possibility of devoting a great deal of attention to these problems inasmuch as their consideration is of independent interest far beyond the framework of this book. Therefore, we will only touch on the very general characteristics of the special features of space which are formed in the environs of Venus, Mars and the largest planet of the solar system -- Jupiter.

The formation of a transition zone -- the ionopause from the diurnal side of the planet in a field located beyond the shock wave at altitudes higher than approximately 300-500 km is the most characteristic feature of interaction of solar plasma with Venus and Mars. There are no radiation bands on them. The ionopause is formed in a zone where the pressure of the solar wind (comprising for Venus approximately one hundred billionth part of a millibar) approximately equalizing the pressure of the ionosphere charged particles along with the pressure of the intrinsic magnetic field of the planet. In an ideal model of the ionosphere with infinite conductivity of the flux, induced by the flux of solar wind, flow along the surface of the ionopause and the region directly adjacent to it above. Therefore, the resulting induced magnetic field is located outside the ionosphere. Obviously, an approximately similar situation is retained in a more actual case of the ionosphere with finite conductivity inasmuch as the time of magnetic diffusion is considerably larger than the time of change of direction of the interplanetary magnetic field and diffusion of the latter in an un-perturbed ionosphere is negligibly small.

At the same time, the picture of interaction is significantly more complex and has a number of specific characteristics separate for Venus and Mars as was apparent according to the results of plasma experiments on artificial satellites of these planets. The complex character of processes in the field of streamlined flow, besides the formation of the intermediate zone identical with the ionopause also included a sequence of overheating and thermalization of ions, the formation of zones of rarefaction beyond the shock wave and many other /272
special features. In particular, the high temperatures of electrons and ions in the ionosphere of Venus apply to it -- these are approximately, respectively, 5000 K and 1000 K, that is, approximately exceeding by a magnitude the exospheric temperature of this planet. This is evidence of the ineffectiveness of processes of temperature relaxation in distinction from the fact that it is observed on Earth where the temperature of electrons, ions and neutral particles right up to $\approx$500 km do not have great differences. Then, it is surprising that high values of electron and ion temperatures are retained on the nocturnal side on a background of neutral temperature of the cryosphere 100 K. This forces us to look for a mechanism of input of energy on the nocturnal side of the planet and nocturnal ionization which, most probably, is related to the intense dynamic exchange and the processes of electromagnetic interaction.

The magnetosphere of Jupiter is a unique formation in the solar system. In many characteristics, it is similar to Earth, increased by approximately 100 times, so that during observations from Earth its angular cross section reaches 2°. The physical properties of space inside the magnetosphere are determined by the intrinsic magnetic field of the planet, creating a natural barrier for direct penetration into this field of accumulating solar plasma. From the diurnal side, the external boundary of the magnetosphere is 50-100 radii distant from Jupiter, changing within these limits, depending on a fluctuation of the flux of solar wind and on the nocturnal side a magnetic drift is formed which extends to a distance exceeding 5 IAU beyond the orbit of Saturn. Inside the Jovian magnetosphere lie the orbits of the Galilean satellites and Amalthea. The charged particles captured by the magnetic field and forming a radiation band have, in turn, a powerful effect on the topology of the field and the configuration of the magnetosphere (Figure 85). Turning along with the planet, they form in the outer regions where the field is weak a "magnetic disk," slanted from the plane of the magnetic equator toward a plane perpendicular to the axis of rotation.

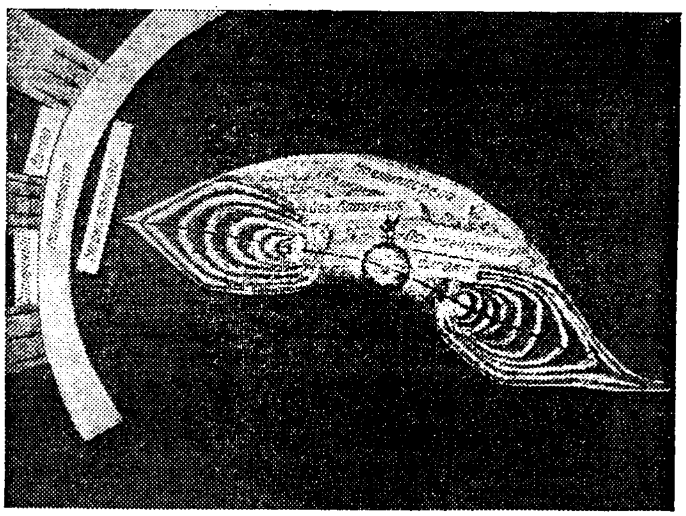


Figure 85. The magnetosphere of Jupiter. On the left, there are separate zones formed on the boundary of the magnetosphere (in front of the radiation bands) with accumulation of solar plasma.

As is known, the main source of particles of the radiation band of Earth is protons and electrons supplied by solar wind and transferred into the inner region of the magnetosphere from its boundaries by the non-stationary electrical and magnetic fields. In distinction from Earth, the basic source of plasma in the magnetosphere of Jupiter, obviously, is Io (which, let us note, differs greatly from the magnetosphere of Jupiter and from the magnetosphere of /273
Saturn). The losses, probably, are determined mainly by scattering of high-speed particles on waves of turbulent plasma excited by the mechanism of cyclotropic instability. Additional losses, obviously, involve powerful acceleration of electrons in the magnetosphere of Jupiter. These electrons which have energies from single units to dozens of millions of electron volts (MeV) with a characteristic 10-hour periodicity corresponding to the period of rotation of the planet, were recorded at distances up to that of the orbit of Earth. Inside the magnetosphere, also the well-known decimeter and decameter radio emission of Jupiter is generated. Flashes of decameter radiation at frequency ≈8 MHz probably involves

plasma instability of the ionosphere or electrical charges in the atmosphere at the same time as decimeter radiation caused by a synchrotropic mechanism; it occurs during movement of the captured /274 relativistic electrons with energies ≈10 MeV between the magnetic poles at distances of ≈1.5-6 radii of the planet. This radiation is modulated with a frequency corresponding to the period of rotation of Io which, probably, is due to interaction with its plasma toroid which was formed by ions of sulfur and oxygen and can itself serve as a source of low-frequency radio emission (with wavelength on the order of a kilometer) recorded by the Voyager craft.

From the toroidal cloud of plasma rotating along the magnetic field of Jupiter, obviously, another remarkable natural phenomenon is involved which is well known to us on Earth -- the aurora borealis. It was observed in the atmosphere of Jupiter during both flights of the Voyager spacecraft at altitudes of 700, 1400 and 2300 km from the visible surface of the boundary of clouds (at the same time that on Earth the aurora borealis basically occurs at altitudes of 100-200 km). A study of the results obtained showed an interesting feature: in the zone of the aurora borealis magnetic power lines are projected passing through the plasma toroid in the orbit of Io. As a result, current tubes are formed which connect the two sides of Jupiter and its near-polar regions. It is assumed that the flows of electrons and ions coming into the atmosphere along the magnetic power lines are intensified by powerful electrical fields. The power of the current flowing inside the current tube is estimated to be on the order of five million amperes.

In conclusion, let us mention one more interesting feature discovered in the magnetosphere of the planet. We are talking about Saturn which has, as we have already noted, a fairly weak magnetic field in comparison with the magnetic field of Jupiter. Therefore, it has a more "modest" magnetosphere and a high degree of uniformity of the magnetic field is apparent in its very symmetrical distribution of the charged particles in its interior zone at a distance of approximately ten radii of the planet. The feature which we have mentioned involves Saturn's rings located inside this zone. It would appear, as was predicted, there are no charged particles within the limits of the system of rings. This phenomenon is called the "guillotine effect," as a result of which a region is formed which has the least radiation of any region in the solar system. The sweeping out of particles occurs as a result of their absorption in material of /275 the rings which they encounter during an oscillatory movement between the hemispheres along the magnetic power lines.

The discovery of this effect by the Pioneer 11 flyby has made it possible, in particular, to put forward a hypothesis about the existence on Saturn of outer ring E which was previously unknown; it is located within limits of approximately 8 R_S; this was later confirmed by studies on the Voyagers (see Figure 54).

Special Features of the Thermal Regime and the Atmospheric Dynamics

A separate set of problems is the thermal regime of the planetary atmosphere and its dynamics. The thermal regime is determined by the quantity of solar radiant energy incident on the planet (energy illumination) for the calculation of energy reflected inversely in outer space. It depends, in this way, on the distance a of the planet from the Sun and its integral spherical albedo A inasmuch as the inner sources of heat for all of the planets of the Earth group can be ignored (their contribution does not exceed millions of parts of a percent). The value of the flux of solar radiation incident on the standards for a single area of the Earth's surface in the absence of an atmosphere defines the solar constant E_s equal to 1.96 cal/cm^2·min or 1365 W/m^2. An important parameter which is used as a measurement of the energy coming into the planet is expressed by these three values and the constant of the Stefan-Boltzmann law σ -- its equilibrium (effective) temperature is $T_e = [E_s(1 - A)/4\sigma a^2]^{1/2}$. Here a is expressed in IAU and the 4 in the denominator takes into consideration the circumstance that energy is incident on the disk and is emitted from the sphere. The values of effective temperature for all the planets are presented in Table 5. Then the values of temperature T_{av} are presented defined as the average between temperatures of the surface of the level of radiation and values of the so-called constant thermal relaxation Γ whose concept we will discuss below.

The planetary dynamics express the balance between the rate of generation of potential energy due to solar radiation and the rate of loss of mechanical energy due to dissipation. From the point of view of the atmosphere of the planet, often one compares it with a thermal machine in which the heating element is regions of equatorial latitudes and the coolant -- the poles. The efficiency (efficiency factor) of such a machine is low -- it does not exceed single percentages. /276

TABLE 5
EFFECTIVE TEMPERATURE AND PARAMETER
OF THE THERMAL INERTIA OF THE PLANET

Planet	T_e, K	T_{av}, K	$t = \frac{mC_pT_{cp}}{\sigma T_e^4}$
Venus	228	480	$3 \cdot 10^9$
Earth	225	275	10^7
Mars	216	235	$3 \cdot 10^5$
Jupiter	134	160	$\approx 10^9$

Let us make the simplest estimates for the atmosphere of Earth using the values of the solar constant presented above. The flux of solar energy on the surface of Earth is about $4 \cdot 10^{13}$ cal/s or $1.7 \cdot 10^{17}$ W. This means that for just one hour the Sun sends to our planet $\approx 6 \cdot 10^{17}$ kW-hours of energy. In order to best understand how impressive the value is, let us say for comparison that for obtaining it one needs to burn $5 \cdot 10^{9}$ tons of oil! The full kinetic energy of atmospheric movement is retained practically unchanged; it comprised about 10^{21} Joules (about $3 \cdot 10^{14}$ kW-hr) and the rate of conversion of potential energy to kinetic energy is estimated at $2 \cdot 10^{12}$ kW. From this, we soon see that firstly, the typical time for a conversion of energy in the atmosphere of Earth comprises $3 \cdot 10^{14}$ kW-hr/$2 \cdot 10^{12}$ kW ≈ 150 hours, that is, approximately a week and secondly that the efficiency of the atmospheric thermal "machine" is $2 \cdot 10^{12}$ kW/$1.75 \cdot 10^{14}$ kW≈ 1.2%.

The source of atmospheric movement on different spatial scales is the absence of equality between incoming and outgoing energies in specific sections of the planet with a total strict fulfillment of conditions of thermal balance on a global scale characterizing the effective temperature. In other words, the occurrence of horizontal temperature gradients as a result of differential heating must be compensated by the development of large-scale movement with a broad spectrum of spatial dimensions. /277

The one system on the planet created due to identical distribution of solar heat in space and in time depends also on whether there is a mechanism of thermal effect with a large or small period of intrinsic rotation of the planet. From this point of view, Earth, Venus, Mars and Jupiter have fully defined similarities and differences which are apparent in the specifics of mechanisms responsible for thermal balance and processes of dynamic exchange on planetary, meso-scale and local levels.

As a result of thermal expansion caused by the dependence of density of gases both on pressure and on temperature (this property is called baroclinicity), it is more strongly heated and this means a less dense air rises upward and a colder and heavier drops downward. Therefore, at first glance it seems obvious that the increments of pressure occurring due to the difference in insolation and this means the horizontal gradients of temperature (baric gradients) must lead to a regular transfer of air masses (and correspondingly, an excess of heat) from the tropics to the poles. Along the meridian then is formed a gigantic closed convective cell in whose upper part the warm air will move from equator to pole and along the surface -- the cold air from pole to equator. This cell itself is called Hadleyan, named for the well-known English astronomer D. Hadley who in the first half of the eighteenth century put forward and gave a good foundation for the hypothesis that different heating by the Sun of equatorial polar regions must be the basic reason for the general circulation of Earth's atmosphere. At the same time, such circulation symmetrical relative to the equator neither in the atmosphere of Earth nor in the atmospheres of other planets has been established. The reason for this is the presence, due to rotation of the planets, of a strong

Coriolis force whose action is analyzed in detail in school textbooks for physics. In the dynamics of the atmosphere (on Earth and also over the ocean), its horizontal component plays a decisive role, thanks to which the air flows deviate from the direction of the movement to the northern hemisphere on the right and in the southern to the left. As a result, the extent of meridional circulation is strongly limited and Hadley's cell dominates in the Earth's atmosphere only at the lowest latitudes, approximately up to 30° on both sides of /278 the equator. In the atmosphere of the middle and upper latitudes, circulation acquires a zonal character, that is, movement occurs along the parallels. Inasmuch as the primary source of them are gradients of temperature, the winds themselves are called thermal. In the troposphere, western winds blow directed from the west to the east at the same time that in the stratosphere the winds change their direction: in the wintertime, west winds blow, and in the summer, east winds, and here one observes velocities up to 50-100 m/s.

When determining the field of winds, a convenient approximation practically realized in the atmosphere is the concept of geostrophic flux or geostrophic wind corresponding to the condition where gradients of horizontal pressure are balanced by the Coriolis forces. The force of this thermal wind depends on the gradient of pressure and the direction along the line of equal pressure -- the isobar.

The effect of the Coriolis forces on the shape of movement usually is characterized by the Rossby number: $Ro = \frac{u}{2L\Omega\sin\Phi}$ where u is the typical horizontal velocity of movement, L is their characteristic scale, and Ω is the angular velocity of rotation of the planet, Φ is latitude. In other words, this is a dimensionless parameter which is the ratio of members related to acceleration (as a result of the baric gradient) and the Coriolis forces in equations for conservation of a pulse. This means that the Coriolis forces are predominant when $Ro \ll 1$. For example, for Jupiter, with values typical in the middle latitudes $u \approx 100$ m/s and on a scale of $L \approx 10^3$ km, this condition is knowingly fulfilled and the flux has a clearly pronounced zonal character.

But this system is very idealized. The actual character of circulation is determined by the accumulation of several types of movement, whose degree of non-ordering strongly depends on angular velocity of rotation of the planet. Wave movement develops on the rotating planet called the Rossby waves. With an increase in angular velocity and with large gradients of temperature along the meridian, also the waves become unstable and with their destruction vortices occur. In the atmosphere of Earth, the dimensions of these vortices /279 change in broad limits from very fine on the order of millimeters to several thousands of kilometers in cross section.

Small and average vortices are elements of atmospheric turbulence and the very largest form well-known fields of low and high pressure -- cyclones and anticyclones. In the cyclones, circulation of air occurs around the center of low pressure in the direction counterclockwise in the northern hemisphere and clockwise in the southern; in the anticyclones, the direction of rotation around the center of high pressure is the opposite. Their lifetime in the atmosphere on the average corresponds to an estimate we made earlier of the rate of conversion -- on the order of a week. Instability of the Rossby waves related to large-scale systems of weather (or, as we already have said, the baroclinic instability), the most effective mechanism is mixing of the atmosphere in a meridional direction, transfer of heat from the equator to the pole and smoothing out of the appropriate differences in temperature on the surface of Earth. At the same time, some of the damping excitations transfer kinetic energy to the average zonal flow (mainly existing at high altitudes in the troposphere of a jet stream) which additionally facilitates the development of circulation.

In studying the complex structure of circulation in the atmosphere of Earth, the component basis of dynamic meteorology and a certain reliability in prediction of weather retains many unsolved problems still. The basic difficulties involve the impossibility of adequate description of fields of pressure and wind depending on a certain influx of solar heat in the field of temperature and characteristics of the underlying surface. Solution by numerical methods of a system of hydrodynamic equations with limitations of initial data about the fields of meteorological elements and unavoidable filtration of a number of harmonic waves in baroclinic models does not permit, to a full degree, calculating all of the varieties of mutually-caused phenomena occurring in the atmosphere.

One runs into even more difficult situations in attempts to have theoretical modeling of circulation on other planets. The position here is exacerbated by the incomparably small volume of experimental data and in a number of cases (for example, for Uranus and Neptune) they are completely absent. Nevertheless, in a theoretical description of the principles of movement observed on Mars, Venus, and /280
Jupiter, there is considerable progress. Models which take into consideration the specifics of conditions on these planets, moreover, help us to better understand the many characteristic features of the dynamics of the atmosphere of Earth.

Certain simplified concepts about movement in the planetary atmospheres can be compared using expressions of similarity and in complex hydrodynamic problems. This approach was developed in the 1970's by Soviet scientist G. S. Golytsyn. It is based on selection of criteria of similarity which are a combination of several dimensional parameters characterizing the mechanical and thermal properties of the planet and a number of universal constants . The use of the indicated criteria appropriate to atmospheric and ocean circulation on Earth have made it possible to reproduce with good precision the quantitative estimates of the rate of appropriate movement. Good justification of the values predicting this theory were also obtained for atmospheres of other planets which were studied during flights of spacecraft.

In an analysis of the thermal regime of the planetary atmosphere usually one uses the concept of a constant thermal relaxation τ

characterizing reaction time of the atmosphere for thermal excitation. This constant is the ratio of the heat content of a single atmospheric column to the value of emitted energy proportional to the fourth degree of effective temperature, that is, it characterizes time in which the reserve energy is de-excited (in Table 5, m is the mass of the column, C_p is heat capacity with constant pressure).

On Venus and Jupiter, similar values of constant thermal relaxation (see Table 5) and the atmosphere itself are optically dense, strongly weakening the solar and intrinsic retained thermal radiation. At the same time, the atmospheres of Earth and Mars are practically transparent for the incoming solar radiation and constant thermal relaxations in them by two to four magnitudes less. At the same time, they have identical lengths of the day and depth of seasonal changes. Basic differences among these planets comprise the character of reaction of surface temperature for daily and seasonal changes and in time differences the radiation equalization of /281
temperature which on Mars occurs almost a magnitude faster. If due to Earth oceans acting as powerful accumulators of heat, the maintenance of an average surface temperature is guaranteed in any latitude close to an average annual value and the atmosphere tries to distribute heat almost uniformly by latitude, then on Mars as a result of low thermal inertia of soil and low thermal capacity of the atmosphere, the surface temperature is close to its local radiant-equilibrium of value at each point on the planet. Due to this, a daily component wind velocity is clearly pronounced.

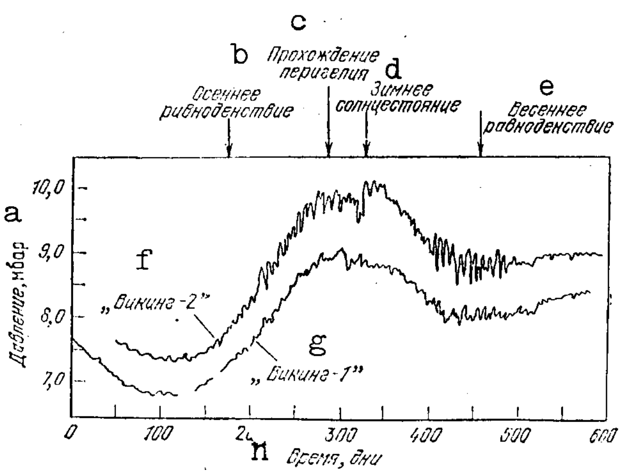


Figure 86. Seasonal variations of partial pressure of CO_2 in the atmosphere of Mars due to accumulation of carbonic acid in the polar caps (according to S. Hess et al.).
Key: a. pressure, mbar;
b. autumn equinox; c. passage of the perihelion; d. winter solstice; e. spring equinox;
f. Viking 2; g. Viking 1;
h. time, days.

An important meteorological factor in the Martian atmosphere is the clearly expressed seasonal variation of pressure as a result of condensation of carbon dioxide in the winter polar cap. This effect is detected experimentally in both landing areas of the Vikings and is shown in Figure 86 cited by us from the original work by the well-known meteorologist S. Hess and his colleagues. The observations encompass almost the entire Martian year in the northern hemisphere of the planet. The deepest minimum of pressure (approximately 120-th day from the beginning of measurements) corresponds to maximum accumulation of CO_2 at the end of winter on the southern polar cap and the other minimum (the 430-th day) -- is freezing on the northern cap. These minimums appear to be close to the autumn and spring equinoxes at the same time that the maximum pressure was observed close to the perihelium during the winter solstice. Restructuring of the circulation system is related to the general change in pressure and local fluctuations indicate a change in the wind regime including the occurrence of dust storms.

It is interesting to note in this connection a certain analogy between Mars and Io: the most probable components of its very rarefied atmosphere made up of sulfur dioxide ($\lesssim 10^{-12}$ bar), obviously, is found in equilibrium with the broad deposits of SO_2 on the surface in the solid phase.

According to the results of measurements of temperature of the atmosphere of Mars in the infrared range, according to the data of the shift in dust on the surface and data of direct measurements from descent modules obtained estimates of intensity and the shift in wind direction in different periods of time. In the summer, in tropical latitudes at altitudes of 15-20 km, western winds predominate with velocity 30-50 m/s at the same time that in the troposphere on the surface, the wind direction undergoes strong 24-hour changes and the average daily component is small, less than 10 m/s. The highest velocity (on the order of 70-100 m/s) of wind is achieved during strong dust storms, usually coinciding with periods of opposition of Mars. Measurements made during a dust storm in 1971 which lasted for about four months made it possible to discover a number of interesting features of this unique natural phenomenon which has a global character. The dark clouds of dust rising up to 10 or more kilometers were observed on the entire disk completely smoothing out the contrasts on the surface. A significant darkening of the atmosphere itself was detected and a lower temperature of the surface (inclination of the temperature profile toward the isothermic) as a result of lack of transparency of the atmosphere for solar radiation which was maintained by the dust. The density of dust particles in the atmosphere with average dimensions 5-10 μm comprised about 10^{-9} g/cm^3. This means that in the atmosphere more than a billion tons of dust were raised whose spectral characteristic in the high content (about 50%) of silicon oxide approximately corresponded to the /283 composition of the surface rock. We note that according to the existing evaluation approximately the same quantity (about 10^9 t) of dust annually is ejected into the Earth's atmosphere which with time can be a serious climatic factor.

Another specific feature of the thermal regime and the atmospheric movement is characteristic for Venus and Jupiter. Possessing similar values of time for thermal relaxation, these planets basically differ in their rate of rotation: Jupiter rotates almost two and one half times more rapidly and Venus 243 times more slowly than Earth. Therefore, during the time that on Jupiter zonal flows are determined very obviously with powerful Coriolis component, the rotation of Venus, obviously, has little effect on atmospheric movement. With very great duration of the Venusian days, an important factor which determines the character of circulation can be the difference of temperatures not only between the equator and poles but also between the subpolar and antisolar points.

A few more years ago, lively discussions were held about what mechanism caused in the atmosphere of Venus such a high temperature on its surface. Well Venus receives almost the same amount of energy as Earth in spite of the fact that it is closer to the Sun and illumination of it at this distance almost twice exceeds the solar constant E_S this means that the albedo on Venus also is approximately twice as high and therefore the values of unreflected solar radiation are comparable. We have looked basically at two alternative models: the greenhouse proposed in 1960 by C. Sagan and the model of deep circulation proposed in 1966 by two well-known specialists in the field of physics of the atmosphere and geophysical hydrodynamics, R. Good and A. Robinson. According to the greenhouse model, a certain portion of solar radiation penetrates to the surface and is absorbed by it but radiation of the heated surface occurs on longer (infrared) waves. This thermal radiation is captured by the atmosphere due to the presence in it of three-atom molecules of carbon dioxide and water vapor having in this field of the spectrum strong bands of absorption and also it is screened by clouds which are not transparent for these wavelengths. As a result, the surface and the lower atmosphere are heated and then part of the heat rises upward as a result of /284 convection. The radiant-convective thermal exchange established on the verticals corresponds to the measured adiabatic profile of temperature. Such a model is described similarly abroad by D. Pollack and in our country by V. S. Avduevskiy, the author and their colleagues.

The strongest arguments made by critics of the greenhouse model occurred in the two expressions: first that the clouds of Venus are very dense and the atmosphere is extremely dusty so that solar light does not penetrate to the surface and secondly that it is hardly possible to create the required high lack of transparency for departing thermal radiation. This resulted in bringing to life a model of deep circulation whose historical predecessor was the so-called aeolospheric (or wind) model proposed by E. Epik. Epik proposed that solar energy is absorbed in the upper regions of the atmosphere found in convective equilibrium and is transmitted to the surface of the planet due to friction on it of dust particles during wind movement. Moreover, even the requirement itself of convective equilibrium must lead to a transport of absorbed energy to the lower layers of the atmosphere and the establishment of an adiabatic temperature profile right up to the surface. From this point of view, the addition of a complementary heat source due to friction appears insignificant.

These proposals were taken under consideration by Good and Robinson. They avoided a number of difficulties which had been encountered in the aeolospheric model and they developed an original system of thermal transfer in the deep atmosphere of Venus using an analogy with ocean circulation on Earth. In this model, solar energy absorbed on the surface of the boundary of clouds illuminated by the

Sun is transferred to the nocturnal side due to large-scale movements. The flow of gas in the region of the antisolar point and the rise in the region of the subsolar point are caused, respectively, by its adiabatic heating and cooling. As a result, in the atmosphere, an adiabatic temperature gradient is established where the atmosphere is deeper the higher the temperature of the surface is.

Direct measurements of illumination on the Venera stations showed that a significant portion of solar radiant energy coming to the planet in actuality passes through the clouds and reaches the surface. Measurements brought us to the conclusion that in the clouds no more than half of the light flux is retained and that the surface absorbs /285 about 100 W/m^2 or approximately a sixth of the energy coming to Venus.

Thus, the first serious expression against the greenhouse model was removed and moreover, one of the chief hypotheses for the model of deep circulation for absorption of solar radiation on the "apex" of the clouds was removed. At the same time, a series of calculations were made in order to analyze the special features of transfer of thermal radiation in the atmosphere of Venus taking into consideration the very strong dependence of the structure of the absorption band of CO_2 and H_2O on temperature and pressure. Interesting results were obtained here by one of the colleagues of the author V. P. Shari. It seemed that even the atmosphere comprising completely carbon dioxide with parameters corresponding to the Venusian provides cover of the main part of the flow of thermal radiation and the addition of water vapor with relative content a total of several hundredths of a percent covers it practically completely. Inclusion in the model of strongly screening clouds consisting of droplets of sulfuric acid increases the effect even more. Then the outflow of heat from the surface and from the lower atmosphere appears to be close to the value of the solar radiation absorbed and agrees well with the values of thermal fluxes measured on the Pioneer-Venus spacecraft.

With further study of this problem by the author, A. P. Galtsev and V. P. Shari showed that the contribution of water vapor in the creation of nontransparency of the atmosphere of Venus required from the conditions of thermal balance appeared to be most significant above approximately 20 km. The experimental (taking into consideration error in measurement) and calculation data on flows of heat can agree with each other having assumed that relative content of H_2O with decreased altitude drops as indicated by the spectrophotometric measurements on the Venera-11 -- Venera-14. But inasmuch as, in adiabatic equilibrium of the atmosphere, there exists a full shift and consequently the ratio of the mixture H_2O/CO_2 in the troposphere must be retained as constant, it is necessary in this case to assume the existence of a certain mechanism which provides evacuation of water vapor from the lower atmosphere. The proposal that it is due to thermal chemical reactions effectively occurring or temperature higher than approximately 600 K seems, however, to be hardly probable.

Thus, we can consider it proven that maintenance of a high surface temperature on Venus is responsible for the greenhouse effect. As to the model of deep circulation, that concept about this mechanism must be additionally made much more specific. /286

Very soon after the appearance of this model, it was pointed out that hypothetical circulation cells encompassing almost half of the circumference of the planet are not stable. Stable circulation can develop only when the necessary conditions have been created for the occurrence of a strong greenhouse effect, that is, when a "super adiabatic condition" of the initial temperature profile on the surface occurs. In other words, the stability of large-scale cells is higher the deeper the solar radiation penetrates into the atmosphere. But it is just this situation, as we know, that is realized in the atmosphere of Venus which has led to the convergence of models which previously appeared to be contradictory.

Thus, there remains no doubt that the main role in the thermal regime of Venus is played by large-scale dynamics due to which equilibrium occurs of temperatures between the equator and the poles between the nocturnal and diurnal hemispheres. Therefore, the greenhouse effect can be considered as a convenient local approximation and possibly as a vital source for the mechanism of planetary circulation on this planet.

Circulation on Venus is traced from the surface of Earth according to the drift of separate irregularities on the surface of clouds during observation in the ultraviolet range of the spectrum. In these irregularities, stable features are retained for a long period of time (several weeks) among which the Latin letter Y is particularly characteristic on the side. The shift of cloud structures of their configurations were studied in detail from on board the Mariner 10 and Pioneer -- Venus spacecraft which transmitted a large number of photo-television images of the clouds (Figure 87). The basic component of movement has an average velocity of about 100 m/s on which other short and long period components and wave processes are accumulated. This average velocity corresponds to a four-day period of repetition of individual configurations which have been called "ultraviolet clouds." They are found at the level of the upper boundary of the main zone of cloudiness and the sub-cloud smoke (Figure 80) and are moved with a velocity almost 60 times greater than /288
the velocity of rotation of the surface of the planet itself.

With the descent of the automated Venera stations into the atmosphere of the planet, measurements of the zonal component of the wind velocity were made by recording the Doppler shift of frequencies of the onboard sensors of the descent vehicles.

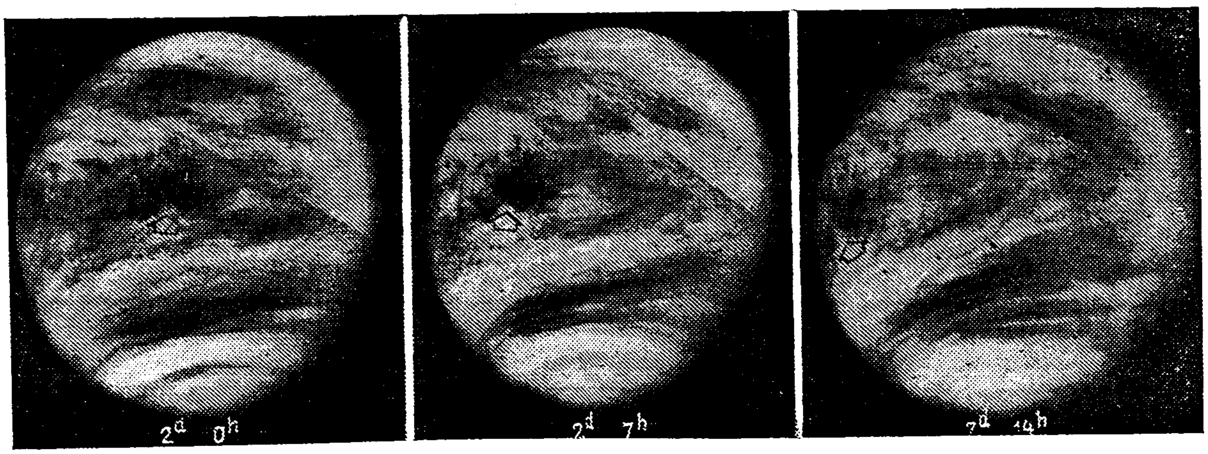


Figure 87. Shift of ultraviolet clouds on the disk of Venus which reflects the character of the four-day circulation in the atmosphere of the planet. The photographs were made by the Mariner 10 at intervals of seven hours for two days after the nearest approach to the planet.

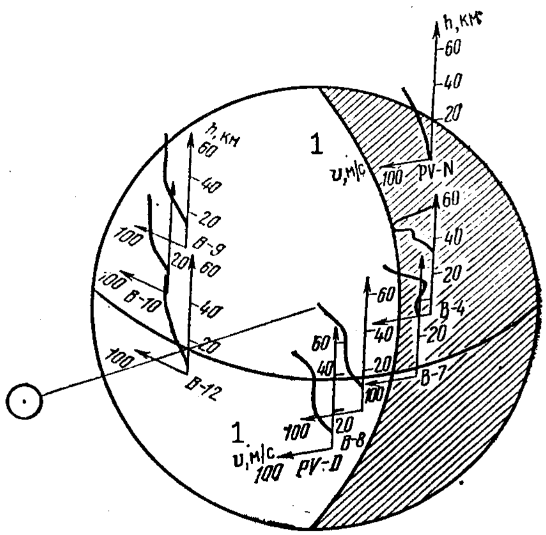


Figure 88. Altitude probe files of the velocity of zonal wind in the atmosphere of Venus according to measurements on the Venera stations and the Pioneer-Venus probes PV (N -- nocturnal and D -- diurnal). A stable character of movement is apparent with small variations depending on the time of day and the latitude.
Key: 1. v, m/s.

In a series of experiments made by V. V. Kerghanovich with the participation of the author and his colleagues, it was established that on the surface the wind velocity is very small and with an increase in altitude grows rapidly reaching velocities of shift of the ultraviolet clouds at a level of 50-60 km, that is, approximately where they are regularly observed. This character of movement with large variations in the wind velocity was retained in different regions of the planet where a descent of our Venera vehicles took place and also later the American Pioneer -- Venus probes; this is well illustrated in Figure 88. This has led to the conclusion that there is a single circulation system on Venus encompassing the entire troposphere and stratosphere of the planet with precisely marked zonal and relatively weak (5-10 m/s) meridional components which is confirmed according to the drift of balloon probes in the Vega-1 and Vega-2 experiments. The greatest wind velocity on the surface /289

(Ø.5 -- 1 m/s) was measured by V. S. Avduevskiy with his colleagues using the cup-shaped anomometers on the Venera-9 and Venera-1Ø.

The phenomena of four-day circulation is a complex problem and has not yet ended although many attempts have been made to clarify it within the framework of different hydrodynamic models. The most realistic for us seems to be the mechanism proposed by R. Thompson in which the development of primarily occurring fluctuation instability is proposed in the large convective cell of the Galilean type to which horizontal perturbation is applied (wind profile). Stability of circulation is guaranteed here due to transfer by pumping energy of convective movement to the energy of the zonal flux. The principle reality of this mechanism was proven by a series of numerical calculations made by colleagues of the author V. G. Vasinym. Within the framework of this theoretical model, in particular, a number of effects were successfully reproduced which had been observed in experiments with Mercury enclosed in a container with a toroidal shape heated from above by a slowly moving gas torch. The latter simulated the Sun at the same time that the Mercury which was found in the limited volume was able in the best manner to model parameters on which the dynamics of the atmosphere of Venus depend.

Additional information on the thermal mode and dynamics of sub-cloud atmosphere of Venus were obtained by experiments in the infrared spectrometry accomplished on the Venera-15 and Venera-16 artificial satellites jointly with scientists in the USSR and the GDR. On each of the satellites an instrument was installed called a Fourier spectrometer which makes it possible to record, with high resolution, the spectra of outgoing radiation (in a range from 36-6 μm). Analyzing the spectral characteristics of this radiation, it is possible to establish a profile of temperature over the clouds, to identify atmospheric components and study variations in the thermal flux in different regions of the planet, that is, study a number of physical principles which determine the special features of planetary meteorology. Significant changes in the altitude of the position of the upper boundary of clouds observed on the Pioneer -- Venus satellite were confirmed; here basically outgoing radiation is formed and also a general tendency toward heating of the polar regions in /29Ø comparison with the middle latitudes. The latter is explained by the descent of the clouds into the polar zone and, obviously, is explained by the descending movement at the center of the cyclone vortex existing here related to the general system of the four-day circulation on Venus. Using the temperature profiles which have been established, it will be possible from the conditions of geostrophic balance (thermal wind) to obtain with time a more detailed picture of horizontal movement in the atmosphere over the clouds.

Circulation on Jupiter and Saturn

Being at a distance from the Sun of about 5 IAU, Jupiter obtains only 4% of the flux of solar energy coming into Earth and Saturn even four times less. The interior flux of heat which we discussed above is even more effective. From the point of view of atmospheric dynamics, these planets have a greater similarity as a result of the very high velocity of their rotation which explains the striated structure at the level of the upper boundary of the clouds observed. It is possible therefore to confirm that movement in the atmosphere of Saturn has approximately the same character as in the atmosphere of Jupiter.

Astronomers approximately in the past one hundred years have accumulated a tremendous amount of observation material which has made it possible to establish a whole series of the most important principles on the structure of circulation on Jupiter. Much of the new information is provided by measurements made on the Pioneer 10 and Pioneer 11 spacecraft and particularly on the Voyager 1 and Voyager 2 (Figures 89 and 90). The most informative color images were obtained during flybys of the Voyagers. The sequence of photographs with high resolution transmitted every two hours made it possible to discover interesting details in the properties of movement and the structure of the clouds. However, the most important result of these recent experiments is, in turn, considering the fact that concepts based on much more limited material about the dynamics of the atmosphere of Venus in its basic characteristics have proved to be true.

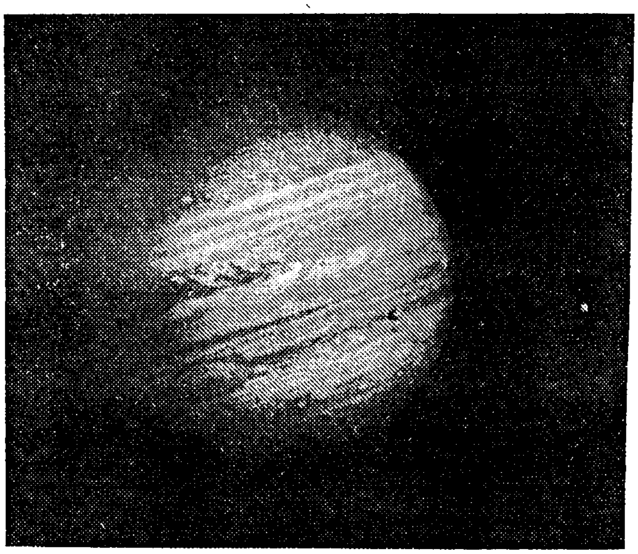


Figure 89. System of zones and bands on the Jupiter disk. Two Galilean satellites are visible: Io and the disk of the planet and Europa on the right (photograph from the Voyager 1).

A characteristic feature /291
of movement on Jupiter is the presence of zonal circulation of tropical and middle latitudes. These flows are well described by a model of a geostrophically balanced thermal wind (we have talked about these concepts above appropriate to Earth meteorology) and circulation itself is axisymmetric, that is, it has almost no difference at different longitudes. The velocities of eastern and western winds in zones and bands comprised from 50 to 150 m/s. On the equator the wind blows in an easterly direction with a velocity of about 100 m/s.

The structure of zones and bands differ in character of vertical movement on which the formation of horizontal flows depends. In the light zones whose temperatures are lower, movement is ascending and the clouds are denser and located at higher levels in the atmosphere. In the darker (red-brown) bands with higher temperature, movement is descending; they are located deeper in the atmosphere and are covered

by denser clouds. The ascending currents in the zones flowing in a
merdional direction on opposite sides, under the effect of the Coriolis
inertia force acquire zonal components directed to opposite sides along /292
the edges of the zone. For instance, in the zones of the northern
hemisphere, the flux directed toward the pole will be inclined toward
the east and directed toward the equator -- toward the west. In the
zones of the southern hemisphere, the picture is a reverse. In this
way, on the northern and southern boundaries of zones with bands, flows
moving toward each other develop and the phenomena of relative
"shifts" occur , the so-called wide shifts which encompass an area
with width on the order of thousands of kilometers. Here wind
velocities are maximum. Energies of the "meeting" flows result in the
occurrence of vortices. The
general concepts about such a
model developed by the
American specialist on
planetary meteorology
A. Ingersoll gives us the
diagram for formation zones
and bands in Figure 91.

Figure 90. Structure of circulation on Jupiter. A mosaic of photographs transmitted by Voyager 1 from a distance of 7.8 million km from the planet. Resolution about 140 km.

With an increase in /293
latitude, the movement
gradually loses its regular
character and above 60°
changes to the greatly
disordered structure.
Obviously, the basic role here
is played by convection whose
source is intake of heat from
the interior inasmuch as
insolation contributing to the
formation of the development
of the system of zones and
bands in the high latitudes
becomes ineffective. The
morphology of individual
details and their evolution
are clearly shown in
Figure 92.

Like Earth, zonal flows
on Jupiter are baroclinically
unstable which leads to the occurrence of long Rossby waves and the /294
formation of vortices with their breakup. Therefore, for regular
movement, vortex configurations accumulate,of the cyclone and
anticyclone type. In the bands, one observes cyclone and in the
zones, anticyclone structures. The most characteristic concept of
them is the Large Red Spot (BKP[LRS]) and numerous spots of smaller
dimensions. Among these, one can isolate white ovals in the middle
latitudes ($\pm 35^{\circ}$) in which, as in the LRS, a spiral structure of clouds /295
is differentiated. Extremely perturbed turbulent regions of flows are
directly related to each of these; here an active role is played by

the wave processes. This is particularly clear in Figure 93 in the zone of the oval located below the LRS.

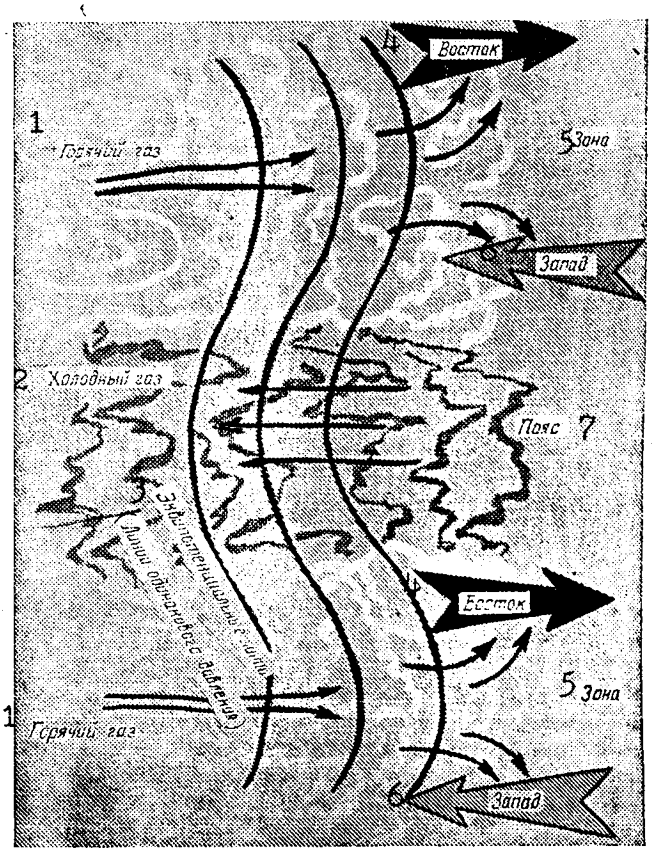


Figure 91. Diagram of the formation of a system of zones and bands on Jupiter reflecting the basic properties of circulation. Key: 1. hot gas; 2. cold gas; 3. equipotential lines (lines with the same pressure); 4. east; 5. zone; 6. west; 7. band.

Similar phenomena including atmospheric vortices in the form of large spots observed similar to the LRS and the white oval, were detected by the Voyager 1 and Voyager 2 in the atmosphere of Saturn. They also have an anticyclone nature. The dimensions of one of these ovals reaches 7000X5000 km and the velocity of movement on its periphery is higher than 100 m/s. These formations, like the ordered structure of zones and bands on Saturn, however, are less clearly expressed due to the extended layer of sub-cloud finely dispersed smoke (Figure 94). Moreover, it appeared that wind velocity on the equator of Saturn exceeds the velocity of atmospheric movement by several times in the near-equator zone of Jupiter, reaching almost 500 m/s (Figure 95). If we recall that the linear structures caused by the 24-hour rotation of the planet, on Jupiter and Saturn are approximately the same (about 10 km/s at the level of the clouds), then on Jupiter it is even somewhat higher, and the reasons for this phenomena remain unclear. Possibly they are related to the fact that in the circulation system on Saturn, deeper regions of the atmosphere are involved with a more intense transmission of the moment of the quantity of motion in the field of equatorial latitudes.

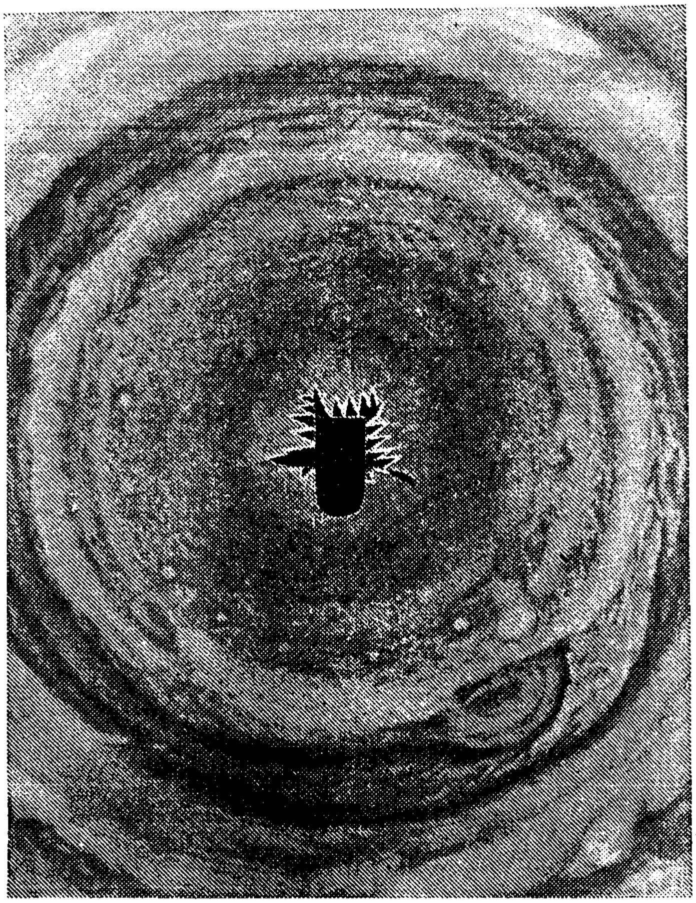
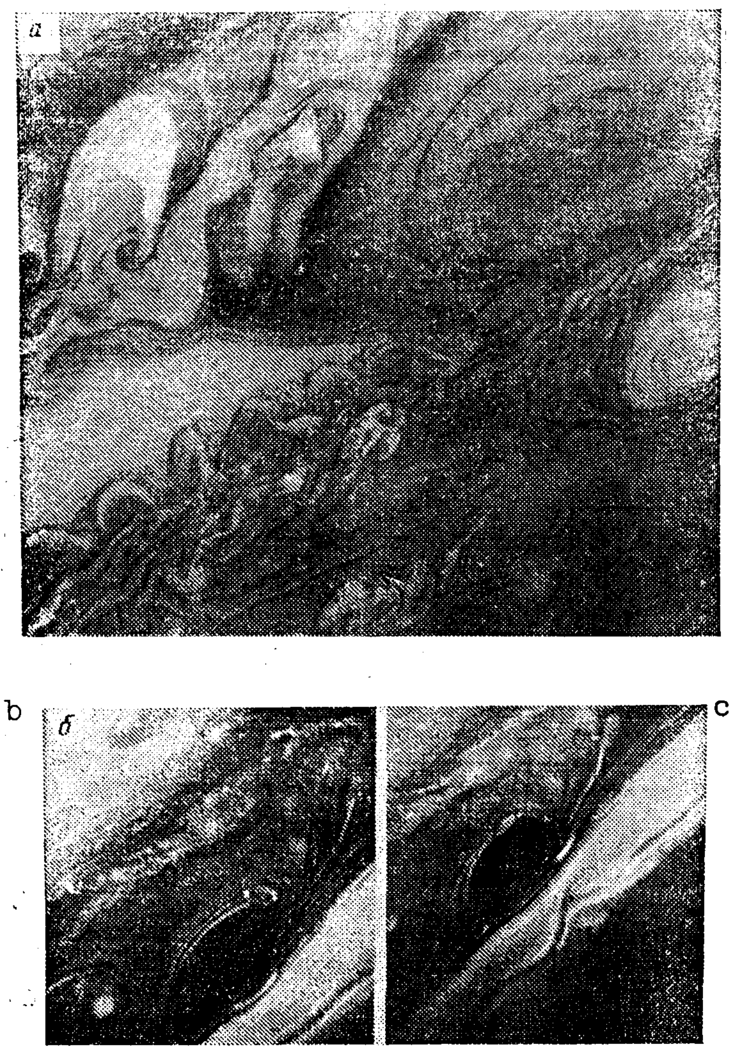


Figure 92. Structure of movement along the South Pole of Jupiter (mosaic of reconstructed photographs of the Voyagers).

We have already discussed the definite similarity of the mechanism of circulation in the atmospheres of Jupiter and Saturn with the circulation on Earth. However, it is necessary to keep in mind that there are significant differences. They are caused primarily by the fact that on the planet-giants there is a significantly smaller gradient of temperature between equator and poles which serves as the basic source for movement in the Earth's atmosphere and moreover a much greater contribution of internal sources of heat from the interior of the planet. For this reason, no noticeable differences were detected in the value of thermal fluxes at different latitudes according to measurements of infrared radiation from spacecraft.

The diagram in Figure 91 corresponds to the concept that the difference in the latitude course of temperature actually serves only as an additional modulator of velocity from which heat comes from the depths. However, a different concept exists which is closer to Earth's meteorology according to which, in spite of the small difference in temperature between equator and poles, movement in the thin upper layer of a gas-liquid planet is generated due to differential heat. This model /296
was proposed by an American specialist on atmospheric dynamics, P. Williams. Its basis is the idea that ordered zonal flows (system of bands more numerous than on Earth) are calculated due to transmission to them of the energy of vortices occurring due to instability, that is, essentially the energy of turbulent movement. Then the rate of conversion of kinetic energy of the vortices and its transmission by a east-west wind on Jupiter must be higher in comparison with Earth's atmosphere. Inasmuch as Jupiter is still colder and this means the quantity of heat which can actually be



b c

Figure 93. Structure of flows inside the Large Red Spot (LRS) under which other light spots are visible. Movement extremely turbulent (photograph from the Voyager 1 at a distance of 5 million kilometers; resolution 95 km)(a). Circulation in the area of the brown spot observed in the atmosphere of Saturn (photographs from the Voyager 2 at intervals of ten hours). Movement, as in the region of the LRS, has an anticyclone character (counterclockwise in the northern hemisphere of Saturn) that is, its region has increased pressure (b).

converted to kinetic energy is approximately 2Ø times less (calculated per unit of area) it is necessary to assume that effectiveness with which the atmosphere of Jupiter converts thermal energy to kinetic, is at least two magnitudes higher /299
than on Earth. On Saturn, the effectiveness of this transformation, probably, had to be even higher.

Independent of which model, in the final analysis, is closer to actuality, the processes of vortex instability are one of the most characteristic of planetary dynamics on Jupiter and Saturn. Therefore, it is necessary to consider in detail the special features of such vortices whose brighter representatives are the LRS (see Figure 93, a).

The Large Red Spot has the shape of an ellipse with half-axes ≈15 and 5ØØØ km. It has already been observed for about 3ØØ years and during this time its dimensions and contrasts have changed repeatedly. In the last 15 years, three times they have undergone a change in activity. The fact that the character of movement inside the LRS corresponds to a regime of anticyclone circulation was discovered at the end of the 196Ø's by following, over a period of several weeks, the shift in the small dark details along the periphery of the spot. Nevertheless,

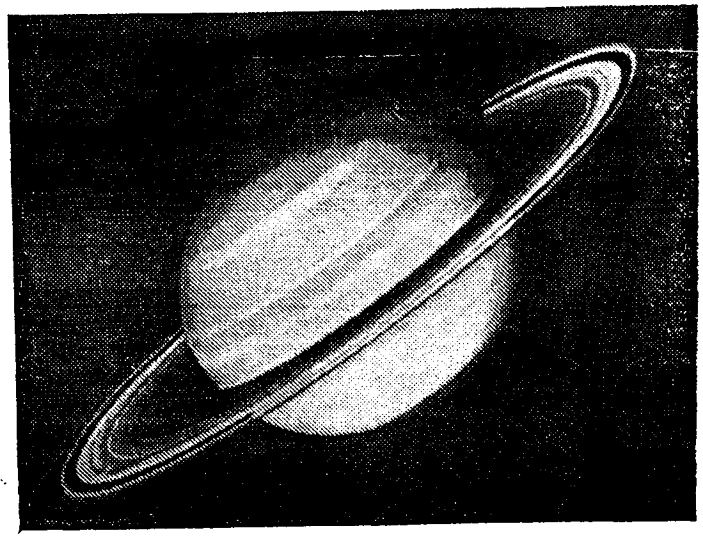


Figure 94. Cloud cover of Saturn. The structure of the zones and bands differ not only precisely due to the extended layer of super-cloud smoke (photograph from the Voyager 2). The large-scale morphology of movement inside the separate spots is indicated in Figure 93, b.

several years later other hypotheses have continued to be energetically discussed relative to its nature. At this time, truly, there are few who believe the hypothesis that this is a tremendous volcano or island floating in a dense atmosphere. A more popular concept is the hypothesis of the well-known meteorologist R. Hyde that the LRS is a perturbation occurring during streamlined flow of a certain obstacle on the solid surface of the planet (the so-called Taylor column). However, besides the proposals about the presence on Jupiter of such a surface (which then everyone certainly did not consider obvious) in this case it must also be assumed that its rotation occurs irregularly. Well, the LRS does not remain in a single position and drifts irregularly along parallel lines so that the period of its rotation differs from the period of rotation of the planet itself. It has been established that in 100 years of observations it has gone around the planet approximately three times.

The hypothesis that the LRS is a free vortex in the atmosphere of an anticyclone type was put forward by G. S. Golitsyn and proved to be the most responsible modern concept. Starting with simple expressions about the increase of energy of circulation with the velocity of rotation and time of transformation of energy (which on Jupiter, in comparison with Earth is many times larger), he evaluated the characteristic period for the regime of circulation on Jupiter within /300
limits of 100,000 to millions of years. Atmospheric vortices, obviously, exist for a more limited time; however, they are significantly larger than cyclones and anticyclones on Earth. Estimates for the LRS give a time on the order of several thousands of years and for smaller vortices -- dozens of years. One must emphasize that the fact itself of long-term retention of such configurations and the entire structure of flow on the disk of Jupiter still does not have an adequately strict theoretical foundation and applies to more difficult problems of geophysical hydrodynamics.

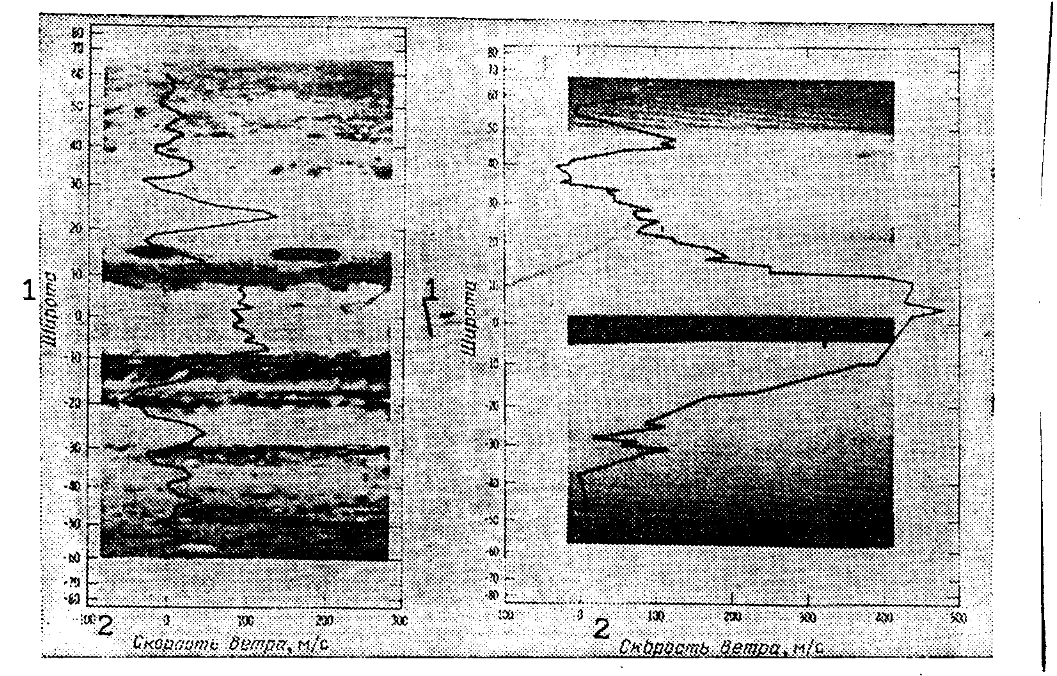


Figure 95. Fragments of the disks of Jupiter and Saturn in equatorial and middle latitudes with profiles characterizing the velocity of zonal movement applied on them. Wind velocity of the equator on Saturn (on the right) is almost five times greater than on Jupiter. Key: 1. latitude; 2. wind velocity, m/s.

The period of rotation inside the LRS comprises about 7 days. The dynamics of flow in its environs is very interesting; it was possible to study them in detail according to photographs from the Voyagers. The small spots (similar to those by which the character of circulation in the LRS was studied from Earth) usually approach from the east. Some of them immediately are deflected toward the north and later on are directed toward the eastern flow going out of the zone of the LRS. Others drift toward the west along the upper boundaries and are maintained on the western edge and then either leave the zone of the LRS farther to the west or are captured in its peripheral flow. On the eastern edge, the spot sometimes splits and one of its parts continues rotation around the LRS and the other drifts toward the east.

Finally, in relation to the discussion of the structure and properties of the LRS, we mention one more interesting phenomenon observed on Jupiter and Saturn in the fields of zones where, as we have already discussed, a rapid rise of gases occurs from the depths due to convection. We are talking about bright white clouds occurring in equatorial and average latitude zones -- because of their shape, they are called "plumage" comparable to colored feathers in headgear. The dimensions of such clouds comprise several thousands of kilometers and inside have separate elements with cross sections of 100-200 km. In their morphology, they remind one of familiar cumulus clouds greatly differing from the diffuse wavy formations on the background around them and they exist for no more than 100 hours, rapidly disappearing. Judging according to temperature, these clouds are located approximately at the same levels as the cloud structures comprising warmer material including the apex of the LRS which is colder than the surface of the band. This fact itself is strange inasmuch as from the red-brown spots on Jupiter's disks, like the analogous color of bands, usually fields of descending movement are /301 involved located deeper in the atmosphere where the temperature is higher.

How do we explain this contradiction? Obviously, the mechanisms of formation of "dark" clouds and "plumages" are different. The occurrence of the latter, possibly, due to wavy processes (the passage of a "propeller wave") accumulated on the basic zonal flow and amplifying convective activity similar to that observed in tropical latitudes on Earth. At the same time, the proposal that the presence of ascending convective movement in the fields of red-brown clouds, primarily in the zone of the LRS, can prove to be illusory. Seemingly the results of analysis of the data of the Voyagers which did not discover a noticeable change in altitude in the structure of flow within the LRS actually indicate this. This problem directly related to the origin and evolution of vortices in the atmospheres of Jupiter and Saturn still need to be solved.

Certain Problems of Climatic Evolution

In the sets of atmospheric parameters averaged for fairly large space-time intervals, statistical principles are apparent which determine climate on the planet or in its separate regions. From the point of view of problems of climate including as the most important problem a study of paleoclimate and prediction of the future weather on Earth, primary interest is given to the two neighboring planets -- Venus and Mars. As a corrected concept in the riddle of development of their climatic evolution, usually one uses the hypothesis we have already mentioned that gases of solar origin were lost at the stage of accumulation of the Earth planets and the initial composition of matter degasified from the interior was approximately the same and that in the future the decisive effect on the course of evolution was the distance of the planet from the Sun. These ideas were developed by A. P. Vinogradov, I. Russel and K. Birch, by D. Pollack and other scientists.

Of course, from all of the planets of the Earth group, the /302 greatest interest for climate is caused by Venus. There are two basic reasons for this. Firstly, as the closest analog to Earth, it is completely natural to consider it as one of its limiting models and it can be used in the future as a unique proving ground for experiments on the active effect on climatic processes on a global scale. In this way, for studying Venus the problem is immediately involved of a purely Earth utilitarian one -- finding the limits of regulation in the nature-climate mechanisms and interrelationships of the

C-3

continuously expanding anthropogenic effects on climate which could appear to be irreversible. Secondly, it is necessary to understand why the two neighboring planets which in the scale of the solar system are found at not too great a distance from each other and are almost identical in dimensions appear to be so different from each other.

Most of the problems -- climatic and cosmogenic -- are closely related to each other. They engender a number of key questions including those which we have mentioned as the most important. Were such clearly different present-day natural conditions of Earth and Venus caused by the character of fractionation of matter of the protoplanetary nebulae or the principles of subsequent stages of evolution caused by different distances of these planets from the Sun? When did the existing climate on Venus appear and was it stable during the time comparable to the development of the solar system or did Venus undergo more favorable periods, for example, in those same epochs when Earth went through the great ice ages? Finally, are the processes of volcanic and tectonic activity completed or are they continuing -- those accompanied by intense degasification and what was the balance of products of degasification and dissipation of gases from the atmosphere of Venus in different eras?

For an answer to the questions posed involving the many general problems of planetary physics, geophysics and climatology, of primary importance is the multifaceted geology-geochemical studies of Venus and other planets of the Earth group, the discovery of more characteristic features in the chemical composition of their atmosphere and surface rock, the study of mechanisms of the lithosphere-atmosphere interaction, radiant heat exchange and atmospheric dynamics. Here, mathematical modeling of complex planetary processes plays an important role as well as the conduct of /303
numerical experiments on climatic models.

It seems we must recognize that Earth was the "luckiest" because it was 10-15 million km closer to the Sun (a quarter of the distance between orbits of Earth and Venus) and otherwise such favorable climatic conditions could hardly have occurred. Here the following simplest evaluations are confirmed which agree well with the strictest theoretical models.

If we assume that the primary albedo of Earth was determined on the whole by the surface and corresponded to the lunar (~0.07), then with the present-day level of illumination of the Sun, its effective temperature is equal to 275 K. At this temperature and with establishment of a comparatively low pressure (about 5 mbar), our planet can retain its water whose main mass was condensed in the atmosphere and dropping on the surface was concentrated in the oceans. As to carbon dioxide, in conditions of comparatively low temperature it accumulated in the Earth's hydrosphere and in the carbonates of sedimentary rock due to bonding with metal oxides making up the minerals of the ocean crust in the upper mantle and partially in a biogenic way due to deposits of calciferous skeletons of marine organisms. The basic non-biogenic process occurs in reactions of carbon dioxide dissolved in water with the well-known minerals --

olivines (orthosilicates) containing iron and magnesium and plagioclases -- anorthotites (alumosilicates) containing aluminum and calcium. As a result of these reactions, minerals were formed (aqueous silicates) containing hydroxyl groups (OH) -- serpentine and kaolin. Therefore, the first of the reactions correspondingly is called serpentinization and the second -- kaolinization.

Here, it is important in general to emphasize the role which, according to the existing concepts, gets around the reactions of hydration in low-temperature stages of condensation of protoplanetary matter. During interaction of olivine-pyroxine groups of minerals with water vapor, hydrated silicates are formed such as serpentine, talc, tremolite, which are most widespread in carbonaceous chondrites. These silicates are the basic latent reservoirs for water subsequently driven off from the interior of the planet. What has been said makes it obvious that it is necessary in this case, for example, for Earth to look at the origin of its atmosphere and hydrosphere as genetically /304 related, as a single evolutionary process.

Let us turn to our model estimate. The value obtained of temperature here is increased inasmuch as it does not take into consideration the fact of the increase of illumination of the Sun which over a period of ≈2.3 billion years according to different estimates spend 35-60% and also the increase of the albedo of Earth from the beginning of formation of the atmosphere. Modern theories of stellar evolution have led to the conclusion that after ≈10 million years after formation of the Sun, it has undergone the basic sequence of the Hertzprung-Russell diagram. However, without taking into consideration the increase in illumination, the average temperature of the Earth's surface appears below the point of freezing even of ocean water. But this contradicts the modern geological and paleontological data according to which primitive photogenic autotrophic organisms occurred on Earth at least ≈2.5 billion years ago. This period includes the most ancient stromatolites -- the stratified formations in thick layers of limestone and dolomite formed as a result of the life activity of bluegreen algae.

The contradiction can be eliminated, assuming that in the early precambrian Earth atmosphere, besides carbon dioxide and water (and probably also methane and hydrogen sulfide), there was a relatively small quantity of ammonia (on the order of a few ten thousandths of part of a percent) or that in it a large quantity of hydrogen was accumulated (on the order of 1 atm). Using any of these hypotheses, one can elevate the temperature above the freezing point for water due to the strong greenhouse effect created by these components as was proposed in the model of C. Sagan and G. Mullen.

For Venus, with this same quantity of the initial albedo, the equilibrium temperature appears to be at least 325 K which is right up to a pressure of 0.2 atm above the boiling point for water. In this way, in order to retain water, Venus would have had to have almost two magnitudes denser an atmosphere than the initial atmosphere in comparison with Earth which with identical rates of degasification of matter of the mantle and dissipation of the atmosphere into the surrounding space is hardly probable. It is more likely that one should assume in the atmosphere there was a gradual accumulation of carbon dioxide along with water vapor. This, in turn, facilitated a further increase in the temperature of the surface due to the greenhouse effect and conversion of all large quantities of CO_2 and H_2O into the atmosphere right up to an equilibrium state determined by carbonate-silicate interaction in the upper layer of the crust of the /305 planet.

Equilibrium between the partial pressure of carbon dioxide and the content of carbonates in the crust is one of the most characteristic phenomena of chemical interaction between the atmosphere and lithosphere of the planet which was indicated for the first time by the most important of American geochemists, G. Urey. In reactions with silicon acid of carbonates the most common of which on Earth are calcites and magnesites (dolomites), carbon dioxide is generated and silicates of calcium and magnesium form relating to the groups of salts of siliceous acid mentioned -- pyroxines and amphiboles and the corresponding wollastonites and enstatites mentioned. Therefore, the relationship between the content of carbonites in the crust and CO_2 in the atmosphere often is called the wollastonite equilibrium. These reactions have an inverse character. According to the diagram of wollastonite equilibrium, the quantity of carbon dioxide related to the sedimentary sheath of Earth and estimated at $3.7 \cdot 10^{23}$ g is comparable to the content of CO_2 in the atmosphere of Venus at a temperature of 750 K ($4.8 \cdot 10^{23}$ g). The latter value corresponds, in this way, to the level of heating in which carbonates became unstable mineral forms on the surface of the planet and their disintegration occurred (Figure 96).

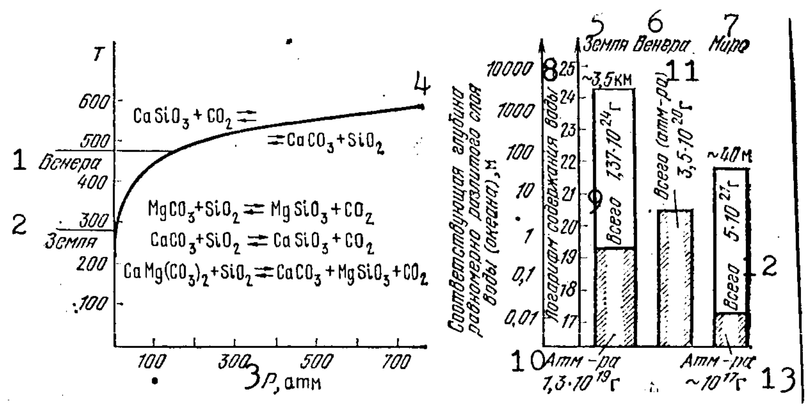


Figure 96. Diagram of the wollastonite equilibrium and content of water (included in the atmosphere) on planets of the Earth group. Temperature T is presented in the celsius scale.
Key: 1. Venus; 2. Earth; 3. R, atm; 4. corresponding depth of uniformly varying layer of water (ocean), m; 5. Earth; 6. Venus; 7. Mars; 8. logarithm of the content of water; 9. total of $1.37 \cdot 10^{24}$ G; 10. total (atm -- ra) $3.5 \cdot 10^{20}$ G; 11. total $5 \cdot 10^{21}$ G; 12. atm -- ra $1.3 \cdot 10^{19}$ G; 13. atm -- ra approximately 10^{17} G.

It is much more complex to explain the situation with water. When assuming a "geochemical similarity," of the processes of evolution of planetary interiors and degasification of the volatile substances, the quantity of water distilled on Venus had to correspond to the volume of the Earth's hydrosphere which comprises approximately 1370 million km^3 or more than $1.37 \cdot 10^{24}$ g. Moreover, on the surface of Venus, water is not retained inasmuch as the temperature there is higher than the critical level equal to 647 K. This statement remains true for aqueous solutions (brines) for which critical temperature usually is somewhat higher (≈675 -- 700 K). As to the atmosphere, then one takes into consideration the values put forward earlier, taking the average content of water vapor as 0.05%, the quantity of water appears to be equal to $3.5 \cdot 10^{20}$ g. This significantly exceeds the content of water in the Earth's atmosphere (≈$1.3 \cdot 10^{19}$ g) but by a magnitude of three and a half is smaller than the reserves of water in the hydrosphere (see Figure 96). /306

Of course, then one must keep in mind two additional expressions. In the first place, similarly to Earth, a certain quantity of water can be retained in the Venusian crust -- both in the form of chemically bonded (constituted and crystallized) water of minerals and in the free (gravitation) water obviously, found in a vapor-like state. The content of water in the Earth's crust according to different sources is estimated from 4-5 to 30-50% of the mass of the hydrosphere from which about 25% is found as the portion of bonded water. Appropriate to Venus, more probable is the lower of the indicated limits due to retention of primarily bonded water. For the possibility of formation of its rock from a moist melt (at 1-1.5% H_2O in the initial material) in particular, data of analysis of soil on the Terra Aphrodite indicates this. Secondly, much water can exist in the mantle of Venus. We have already discussed the fact that according to A. P. Vinogradov's hypotheses, only a small portion of the volatile substances contained or produced in the mantle of Earth were degasified into the atmosphere and hydrosphere for the entire geological history of our planet. In particular, the volume of the hydrosphere according to his estimate does not exceed 7.5% of the total reserves of water in the mantle. If this estimate is approximately true for Venus (with similar character of thermal evolution of both planets), then the potential possibilities of "being acquired" by the hydrosphere in the case of a change of climate on Venus are retained.

Other processes of climatic evolution, obviously, occurred on Mars. Its equilibrium of temperature is significantly below zero and the water distilled from the interior can be found on the surface in a liquid state only with an adequately dense atmosphere thanks to the greenhouse effect and the increase in temperature. It is difficult to answer the question of whether water existed on the surface of Mars only at a certain stage of evolution or whether it appeared regularly over a long period of time, but its traces remain in the form of shriveled river channels and glacial scouring (exaration) and are fairly obvious. /307

In this case, one must add that on the planet at the same time a sharp change occurred in climate probably somewhere within the limits of 1 billion years ago and that up to this moment Mars had passed through the apex of its geological evolution and was more similar to Earth. This change could have been due to a sharp decrease in the generation of internal heat which is naturally involved in the final stage of volcanic activity on Mars. But it is impossible to exclude the idea that variations in the Martian climate occurred repeatedly similarly to the period of great ice ages on Earth. Hypotheses have even been put forward that they occur right now with a period of several hundreds of thousands to millions of years. These hypotheses are based on calculations made earlier of the periodic oscillations of the slant of the equator of Mars toward the plane of its orbit as a result of tidal perturbations of the planet and the Sun and correspondingly changes in exposure to the Sun on the poles. The variation in inclination of the equator indicated in Figure 6 (upper curve) corresponds to the change in average annual exposure to the Sun on the poles (ratio of their exposure to the solar constant) approximately by a factor of two from 0.08 to 0.18. A significantly smaller effect is indicated for the periodic changes in eccentricity of the Martian orbit (within limits from 0.005 to 0.141) as a result of which exposure of the poles changes by a total of 1-2%. The corresponding models were considered by V. Ward, B. Murray and other scientists. The calculations of C. Sagan, P. Garash and O. Tun led to the conclusion that due to the change in the inclination equivalent to oscillation of illumination by the Sun, there could be two maximum stable states of the atmosphere of Mars: one with such a rarefied atmosphere as there is now and the other with an atmosphere in density equal to that of Earth. The source of increase in density by more than 100 times in this model was the pole on whose polar caps /308
freezing of large quantities of carbon dioxide was proposed. It was pointed out that increased radiation of the poles due to the large inclination of the axis of rotation in comparison with that of the present day (approximately by $4-5^{\circ}$) accompanied by a decrease in their albedo, in principle, is capable of creating such an atmosphere and at the same time lighting up the aqueous ice.

Later measurements made by the Viking, however, did not detect any significant quantity of "dry" ice in the caps in pure form. Obviously, the main mass of degasified carbon dioxide is found in the Martian regolith and also in deposits of finely dispersed dust material around the poles and in the stratified plain regions of the near-polar latitudes. Particularly large stratification of such frozen soil could be expected in the northern polar region due to differences in exposure by the Sun of the Martian hemispheres: in the north, the winter is longer. Nevertheless, in this case, the equilibrium state between the quantity of adsorbed carbon dioxide and its partial pressure in the atmosphere is determined by temperature. Therefore, concepts about the possibility of changing density of the atmosphere depending on the change in inclination of the axis of rotation as whole remain, obviously, true.

Of course, it would be tempting to believe that to us simply Mars would not seem different with a more favorable climate due to inadequately large inclination of the axis of its rotation in the present-day era and that this makes it possible to look at our descendants approximately a hundred thousand years later on. However, opposed to this attractive hypothesis is the fact that covered with water and glacier channels and troughs, obviously, they were formed earlier than the relatively younger craters of impact origin on their shriveled surface whose age is estimated to be at least dozens of millions of years. Therefore, in our opinion, the hypothesis about cyclic changes of the level of illumination of the Sun put forward by the American astrophysicist V. Fowler in connection with attempts to explain the paradox of the solar neutrino deserves a good deal of attention. Thus we mention the considerably smaller (approximately by 5 times) flux recorded on Earth of the neutrino from the Sun in comparison with their expected output as a result of the reaction of thermonuclear synthesis, taking into consideration the main mechanism /309 of generation of solar energy. The correlation found for these cycles repeating with a periodicity of $\approx 10^8$ years with great icing up on Earth in a natural manner could be explained both by periodic oscillations of the Martian climate and possibly significant climatic variations on other planets.

For discovering the paths of evolution of the atmosphere and the ancient climate of Venus and Mars, the results of mass-spectrometric measurements in the atmospheres of these planets are very important; they contain small admixtures primarily of inert gases (see Table 4) and ratios of the basic isotopes. As has already been discussed, by a comparison of measured concentrations of inert gases with their absolute and relative content in Earth's atmosphere and the gaseous fraction of meteorites, one can judge the degree of their primary fractionation at the stage of accumulation and passage through the geological time by the degree of degasification on the planet. An analysis of the isotopic composition makes it possible additionally to clarify the degree of degasification and fractionation of volatile substances during dissipation of gases from the planetary atmosphere.

On Venus, the ratio of the content of the radiogenic isotope of argon Ar-40 to the content of the primary isotopes of argon Ar-36 and Ar-38 are approximately equal to one at the same time that on Earth this ratio is 300 and on Mars, 3000 times greater. At the same time, the absolute contents of Ar-40 on Earth and Venus are approximately the same and on Mars approximately a magnitude smaller. In other words, in comparison with the Earth and particularly the Martian atmospheres, the atmosphere of Venus is greatly enriched with primary isotopes of argon: at this time, both Ar-40 is approximately twice as small as on Earth and Ar-36 is almost 100 times larger. Also, neon is approximately a magnitude larger in the Venusian atmosphere although isotopic ratios for both planets do not differ greatly. The data on krypton and xenon is less definite, nevertheless, in these cases their absolute content on Venus, obviously, is approximately a magnitude greater. Let us add to this that if we take the ratios of measured volumetric contents of primary argon in the atmosphere per unit of mass of the stellar body (for Venus, Earth and Mars, they, correspondingly, equal $5 \cdot 10^{-6}$, $2 \cdot 10^{-8}$ at $0.5 \cdot 10^{-10}$ cm^3/g) and are applied on a graph in a logarithmic scale depending on the distance

from the Sun; then these ratios appear to be located in approximately /310
a single straight line. On this same line, certain types of carbonate chondrites of classes C and H are applied (for C3 it is approximately 10^{-6} cm^3/g and for the higher temperature H, on the average, $2 \cdot 10^{-8}$ cm^3/g).

In this way, we encounter a steady tendency which cannot be random. An explanation of these facts must be, obviously, finding the matter of the planet and meteorites at different distances from the Sun in the condensation sequence of formation which we considered earlier. In this way, the question of evolution of the atmosphere and climate blend into a general cosmogonic problem.

It is possible to add that with different effectiveness three basic mechanisms are active: nonuniform accumulation of planets (heterogenic accretion), nonuniform degree of degasification and fractionation of the primary protoplanetary cloud.

A model of heterogenic accretion was discussed in detail starting with an analysis of the content of volatile substances in the matter of planets of the Earth group and meteorites by E. Anders and T. Owen. According to their idea, after the formation of the basic mass of the planet, on the completed stage meteorites fall on it consisting of later low-temperature condensates containing the main mass of volatile substances in them.

As one gets closer to the Sun, the number of strikes must increase and this means the difference in positioning of the planet can play a significant role in the formation of the reserve of volatile substances and the degree of subsequent degasification of the planet, including the surface layer hit by meteorite matter.

The last condensate, in turn, includes carbonaceous chondrites enriched, as was already noted, by hydrated silicates, gases and even organic matter. According to content of hydrogen in the chondrites, the C3 group is fairly close to the H group of chondrites. Then, assuming an identity of factors for release of primary isotopes of argon and hydrogen on Earth and Venus, it is possible in the hypothesis confirmed above to come to the conclusion that there are comparable quantities of water distilled on the surface of both planets in the geological epoch. For Mars, at the same time, it is necessary to pay attention to its mass, which is approximately 9 times smaller in comparison with the mass of Earth and Venus.

The degree of degasification of the matter of Venus, obviously, was higher than on Earth. Correspondingly, more Ar-36 was accumulated inasmuch as degasification of Ar-40 accumulated gradually on the average at a great depth occurs more slowly than its primary isotopes and this means a larger quantity of volatile atmophilic elements was transferred into the atmosphere of Venus. At the same time, on Mars for the reserve of volatile matter, probably, is depleted in comparison with the corresponding reserve on Earth and Venus, degasification was less complete so that obviously, it is related to a lesser degree of differentiation of Martian matter and the small mass of this planet. Moreover, due to differences in temperatures, the primary isotopes of argon and other volatile substances must basically be found in the Venusian atmosphere in opposition to Mars where they, to a greater degree, were accumulated in solid surface rock.

The expressions presented do not explain fully, however, the data on the unusually high concentration of primary argon in the atmosphere of Venus where as we see its content in calculation per unit of mass of the planet by several times exceeds an analogous content even in the carbonate chondrites type C30 which are most enriched by this isotope. Therefore, the principle observed in distribution of inert gases on planets could be, to a certain degree, caused by the third of the mechanisms mentioned -- by the difference in the initial relationship of the elements during formation of the planets. In this case, it would be necessary to assume that in the process of accumulation, Venus was made up of a preplanetary cloud with greater primary isotopes of argon, neon, krypton and groups of other elements related to them, larger than on Earth and Mars, on the other hand with a lesser quantity. Is it possible for such a sharp fractionation of primary matter to occur in a comparatively small area of the solar system within limits less than 0.8 IAU? It seems to us hardly probable and the question still remains open.

But one way or another, we will find completely determined additional confirmation of concepts about the decisive role of the positioning of the Earth planets relative to the Sun in the course of their climatic evolution. Otherwise, it is difficult to explain why Venus has lost such a tremendous mass of water compared with the volume of Earth oceans and Mars has "conserved" a significantly larger average quantity of water on its surface in the form of ice.

The results of analysis of the content of hydrogen in the /312
atmosphere and its heavy isotope of deuterium are evidence of the fact that Venus had a fairly heavy hydrosphere. This analysis presented according to the data of mass-spectrometer measurements on the basis of the Pioneer-Venus probe by T. Donahue et al. led to an important conclusion: the ratio of deuterium D to hydrogen H in the atmosphere of Venus comprises $(1.6\pm0.2)\cdot10^{-2}$, that is, is two magnitudes larger than in the atmosphere of Earth! Explaining such a high enrichment of the Venusian atmosphere with deuterium can be due to the separation of these isotopes during thermal outflow of hydrogen from the atmosphere where it accumulates as a result of evaporation of oceans and subsequent dissociation of hydrogen vapor by ultraviolet radiation. Then, as we see from theoretical estimates, up until now the relative content of hydrogen in the atmosphere is increased by approximately 2% and effectively acts not as a thermal but as a hydrodynamic mechanism of outflow in which fractionation of hydrogen and deuterium does not occur. This latter idea applies its own type of lower limit to the quantity of water distilled on Venus at the level of approximately a half percent of the volume of Earth hydrosphere so that once again the measured ratio D/H applies. However, it is hardly a real volume of the Venusian hydrosphere which would correspond to this low level; with the consideration of the geochemical expressions presented above,

it is much more probable that it would be approximately the same as on Earth. But one cannot strictly prove this as yet.

The question of the accumulation in the atmosphere of significant reserves of water capable of creating a powerful phase of the greenhouse effect still remains open for a loss of water may have occurred more or less evenly. We have seen that with the modern conditions, the relative content of vapor of H_2O required in the atmosphere of Venus is not low inasmuch as the screening of thermal radiation almost completely is provided by bands of absorption of carbonates due to the modification of their structure at high temperatures and pressures. From this, however, it does not follow that the basic non-transparency was created due to an accumulation of CO_2 at the earlier stages of evolution. But even in a case where the water vapor in the atmosphere has not accumulated and its loss was uniform, one must assume that the flow of molecules of hydrogen required for evacuation of the distilled quantity of water from the atmosphere reached a tremendous value -- about $7 \cdot 10^{10}$ $cm^{-2} \cdot s^{-1}$. This is approximately three to four magnitudes higher than the modern rate of dissipation of hydrogen from the atmosphere of Earth and Venus and the large values in general appear to be unrealistic. /313

Also it is necessary to indicate by which processes the bonding of a tremendous mass of released oxygen occurred. The atmospheric components, even taking into consideration the chemistry of the clouds, could hardly play a decisive role here. It is hardly probable that the entire excess of oxygen went into oxidation of carbon due to the more realistic hypothesis about the primary origin of atmospheric CO_2 due to gasification from the interior. As to the dissipation of oxygen from the atmosphere, here one would require an exospheric temperature higher than 1500 K which is several times greater than the modern value and in conditions of intense radiation cooling by molecules of carbon dioxide could hardly be possible in general. More probably, the oxygen was bonded with surface rocks and this forces us to assume a considerably larger tectonic activity on Venus than on Earth; this would be required for the effective bringing to the surface from the depths of fresh unoxidized material.

Now if we turn to Mars, the results of the isotope analysis and the relationship of volatile substances (CO_2/Ar-36; N_2/Ar-36) gives us the basis for considering that at some time it actually possessed a denser atmosphere approximately 20 times greater in comparison with the existing content of carbon dioxide and approximately 10 to 100 times greater a content of nitrogen. The latter estimate was made on the basis of the measured isotope ratio of nitrogen (N-15/N-14) which appeared to be approximately 75% higher than in the atmosphere of Earth at the same time that the isotope ratios of other extensive components -- oxygen and carbon -- are retained approximately the same as on Earth. This leads us to an important conclusion that even in the most favorable periods, the atmosphere of Mars remained at least ten times less dense than that of Earth and this atmosphere was capable of creating a noticeable greenhouse effect and retaining liquid water on the surface.

The total distilled quantity of water on Mars is estimated at a value of $\approx 5 \cdot 10^{21}$ g which corresponds to the average depth of a uniformly diffuse layer on the surface of about 20 m; this is approximately two /314
magnitudes smaller than on Earth but, however, a magnitude larger than on Venus (see Figure 96). One could expect that almost all of this mass of distilled water is retained right now on Mars in the near-surface glaciers and polar caps if one starts with the hypotheses that the rate of dissipation of atoms of hydrogen for the extent of all geological history of the planet corresponded to the present day value of the flow (about 10^8 $cm^{-2} \cdot s^{-1}$). In this case, the quantity of water lost relating to the thickness of the effective layer must not exceed 3-5 m.

It is interesting to note that besides adsorption on the Martian regolith and in the stratified near-polar regions, one of the channels for evacuation of CO_2 from the atmosphere could have been the compounds of inclusion which we already mentioned -- the clathrate compounds. It is easy to convince oneself that for the quantity estimated above of H_2O and CO_2, the molar ratio for the clathrate compound CO_2andH$_2$O to which it corresponds almost coincides with the lower limit for gaseous hydrates at normal pressure.

A completely natural question can arise: is it only distance from the Sun that affects the climate of Mars and what would happen to it if it were the same dimensions as for instance Earth or Venus? One can assume that in this case Mars would accumulate and maintain a significantly larger quantity of volatile substances (which particularly favors the hypothesis of heterogeneous accretion which we considered) and as a result of any course of thermal evolution, the degree of differentiation of the component matter and degasification would be more complete. Such a Mars, obviously, would possess a significantly denser atmosphere and a moderate climate. Taking into consideration the differences presented above in mass and degree of degasification in comparison with that of Earth, the estimated mass of distilled water would have to increase by at least 25-30 times which would make it comparable with the Earth's hydrosphere with a layer with thickness about 0.5 km.

The composition of the atmosphere of Mars including oxygen, nitrogen, carbon, a temperature close to the Arctic and Antarctic regions of Earth and a richness of water in its upper horizons it would seem, favor the optimistic expectation of observing signs of life on this planet. Unfortunately, biological experiments with Martian soil on the descent vehicles of the Viking established this question as unanswerable or as having more negative than positive /315
results. Obviously in conditions of effective natural sterilization due to shortwave ultraviolet radiation penetrating to the surface (with energy of photons less than 6-7 eV) and the strongly oxidized medium in the soil obtaining oxidized compounds (peroxides), the chances of detecting life on Mars were small.

There is a basis for assuming that a number of apparently positive pieces of information about biological activity in each of the three types of biological experiments on the Vikings -- gas exchange, decomposition of markings and assimilation of carbon (in the two latter cases, using the labeled atoms of carbon C-14) -- are explained by processes of chemical interaction. In particular, the intense generation of oxygen in the initial phase of the experiment on gas exchange most probably involves an excess of peroxides in the soil and not processes of metabolism. An important argument against the presence of live forms also is the extremely low threshold of detection on the surface and in the near-surface layer of organic molecules (10^{-6} by mass according to ratio to the inorganic). Moreover, it is completely possible that the negative result of the mission of the Vikings was determined by the inadequate sensitivity of the methods used in such modern conditions unfavorable for life on Mars. It is impossible, of course, to exclude the fact that these conditions could be considerably more favorable in earlier history of the planet or at certain stages of its climatic evolution when on the surface there was liquid water. Therefore, there was considerable interest in the attempts to detect the simplest forms of paleological life in the Martian soil available by a direct method of analysis in Earth laboratories.

While, there are not any reliable signs of life on Mars to be found of certain planet satellites, primarily on Titan, basically they are retained although the probability of the existence of life is still extremely small. If in the future with such hopes finally settled, then only with great care can the question be posed of why life occurred and developed intensely only on the planet the third from the Sun -- the question has not only a natural science value but also a tremendous philosophical value -- value from the standpoint of attitude.

Can you say who chained
man to the universe?
Had love been true in this world,
the entire earth would have been motherland,
And having a free soul, man would have
equally loved the entire broad world,
And not only the earth would have been the
motherland but also the stars and planets!

A. K. Tolstoy
"Don Juan"

CONCLUSION

The solar system has made available for us unique examples of intricate natural complexes different from our planet itself. Their study in all interactions and depending on certain factors, the discovery of the most important criteria and principles of formation of these complexes has led to establishment of comparative planetology, on whose successful development, in particular, will depend the best understanding of the mechanisms as the basis for nature on Earth and its position as a member of the solar system. /316

The study of the majority of natural processes on examples of different heavenly bodies provides an unusual scope for the approach and simultaneously makes it possible to examine it in depth. New experimental data and the ideas developed from them make it possible to go beyond the limits of the circle of concepts comprised as a result of adherence to some particular point of view or model.

All of this leads to recognition of the commonality of nature of different phenomena. It is adequate to say that the principles of element and mineralological composition of matter in planets and meteorites which have been discovered, the commonality of the character of thermal evolution, volcanic and tectonic activity and geological structures on the planets of the Earth group, the discovery of a deep connection between processes of formation and their mass with the formation of rotational movement, the number of similar features of circulation on Venus and ocean circulation on Earth, the probable correlation of periods of the ice ages and the climatic evolution on Earth and Mars, etc. As a result, it has actually become possible to talk about comparative geology, comparative meteorology and climatology and on a new basis to present the problem of genesis /317 of heavenly bodies which is directly related to general problems of nuclear and chemical evolution of matter in the solar system.

For the approaching generations of our epoch, one of the most important accomplishments of mankind from the point of view of the historical perspective is our entry into space. The possibility has been shown and the beginning has been made for a long-term period for expansion of the sphere of habitation beyond the limits imposed by the region of the solar system -- the Earth planets.

What will happen later on? Space expeditions, landing of people on planets, their making themselves at home there, the creation of lunar, Martian and other permanent active bases? We believe that mankind is going into this new stage but, of course, not in this century. Primarily this is because the possibilities of automatic probes has been far from exhausted and more likely we are continuously expanding them. Another extremely serious reason is that the existing technical means are hardly suitable for interplanetary communication -- they are too heavy, cumbersome and inefficient. We need new engines for space rockets -- nuclear, electroreactive, but, unfortunately, they have not been adequately developed and do not have the necessary thrust. Among other problems, we include the most important which are related to guaranteeing life support and a long-term stay of man in outer space. Finally, one must not forget how many means are required for organizing such an expedition and moreover right now there exist a multiplicity of other problems on our planet whose solution which also requires tremendous expenditure, undoubtedly, have high priority. And must we still talk about the fact that equipping and sending such expeditions must be the result of the collective efforts of the developed countries of the world, an act of international cooperation undertaken in the interests of all people on Earth in distinction from the existing forces for improvement and development of weapons which threaten the very existence of civilization?

Neighboring us is lifeless limitless space, new regions in the form of other planets and asteroids which with time have become a cosmic ocean and will be mastered as the first settlements of the "new light."

Today this can seem to be a fantasy but, undoubtedly, projects /318
for changing in a more favorable direction the existing climatic conditions on Venus and Mars are being developed; settlements will be created on the Moon and asteroids will begin to be developed. As to distances, we remember that Christopher Columbus needed 70 days in order to cross the Atlantic Ocean -- two thirds of the time for a flight of an automated station to Venus. And similarly to this, right now overcoming the distance between Europe and America, it can be measured in hours with the progress in technology we can sharply decrease the flight time to the other planets. At the same time, the degree of risk is being decreased; such communication will become regular and ordinary.

Inevitability of this process is fairly obvious. One must not forget that the level of development of life on Earth has acquired the characteristics of technologically developed civilization only in the last approximately 100 years at the same time that mankind has existed for hundreds of thousands of years. And with the passage of this very insignificant period of turbulent development of civilization, we have begun to perceive the deficiencies in sources of raw materials, energy resources; problems have arisen of overpopulation in certain regions, contamination of the environment, etc. Correspondingly, social problems have been aggravated in conditions of continuously growing rates of scientific and technical progress and economic development. It is undoubtedly true that mankind over a period of three thousand years will face the necessity for mastering new territories in the near environment of out star, the maximum use of its energy output, mastering tremendous resource richness of planets and asteroids.

In this way, the purpose of study of planets is not limited and we have not exhausted the accumulation of knowledge about how our neighbors in this world are constructed and function and how they have occurred and developed. This is one of the sections of fundamental science with which very closely the solution of many technical-economic and social problems will be related on the path toward further development of civilization.

Man and the modern world (limited in its scale and fairly "brittle" in its adaptive capability) with an ever increasing degree is familiar with the achievements of the industrial revolution. A /319 paradoxical situation has arisen: unconsciously finding captivity in it, at the same time he loses the capability of being amazed by new scientific and technical achievements perceiving them often as natural and at the same time stopping imagining the actual prospects and consequences connected to them. Moreover, striving toward what is new, hidden and enigmatic is maintained feeding the human fantasy and right now leading to a mystical type of futuristic thinking about the myths of "space pods," "foreign planet humanoids." We hardly need to point out that these fantasies in themselves don't have the smallest scientific basis and we hope that the content of this book will help us to better understand the various facets and separate reality from fantasy.

But then the prospects for transfer of man to a new stage -- mastery of the solar system -- undoubtedly is scientific, dictated by the logic of its preceding development and its further progress and in its grandiose scale its significance can hardly be truly expressed. It would be an achievement if people on the planet Earth, once and for all having ended their conflicts, would combine their forces for a favorable beginning here. Here is the pledge for further forward movement of human civilization closely related to the embodiment of our communist ideals. At the same time, prospects are expanding for establishment of contacts with other similar civilizations in our galaxy and beyond its limits. It has many times increased the "whispers of Earth" as we call the discussion about our beautiful planet described on special metal records played inside the spacecraft which are destined to leave the solar system. And then this will be a story not only about the cradle of civilization but also a form of expression of our great compatriot, the founder of cosmonautics, K. E. Tsiolkovskiy, and also a description of our near-Sun space which is successfully being made into a single large home.

Mankind is truly the master of his star, the master of other lifeless planets and it is undoubtedly true that the future prospects are good for acquiring their riches. We are talking about the high evaluation for future generations of today's efforts by our contemporaries because these will be the origin of a grandiose path.

REFERENCES

1. Beletskiy, V. V., Ocherki o dvizhenii kosmicheskikh tel [Notes on the movement of cosmic bodies], Nauka Press, Moscow, 1972.

2. Gerels, T., Protozvezdy i planety [Protostars and planets], (in two parts), Mir Publ., Moscow, 1982.

3. Gerels, T., Yupiter [Jupiter], (Parts I, II, III), Mir Publ., Moscow, 1978-79.

4. Goldsmith, F. and T. Owen, Poiski zhizni vo Vselennoy [Search for life in the universe], Mir Publ., Moscow, 1983.

5. Golitsyn, G. S., Vvedeniye v dinamiku planetnykh atmosfer [Introduction to the dynamics of planetary atmosphere], Gidrometeoizdat Publ., Leningrad, 1973.

6. Goody, R. and Dzh. Walker, Atmosfery [Atmospheres], Mir Publ., Moscow, 1971.

7. Grebenikov, Ye. A. and Yu. A. Ryabov, Poiski i otkrytiya planet [Search for and discovery of planets], 2nd ed., Nauka Publ., Moscow, 1984.

8. Kaula, U., Vvedeniye v fiziku planet zemnoy grunny [Introduction to the physics of planets of the Earth group], Mir Publ., Moscow, 1971.

9. Keldysh, M. V., editor, Pervyye panoramy poverkhnosti Venery [The first panoramas of the surface of Venus], Moscow, 1979.

10. Keldysh, M. V. and M. Ya. Marov, Kosmicheskiye issledovaniya [Space research], Nauka Press, Moscow, 1981.

11. Kondrat'ev, K. Ya., Meteorologiya planet [Meterology of the planets], LGU publication, Leningrad, 1977.

12. Ksanfomaliti, L. V., Planety, otkrytye zanovo [Planets discovered anew], Nauka Press, Moscow, 1978.

13. Kulikov, K. A. and N. S. Sidorenko, Planet Zemlya [Planet Earth], Nauka Press, Moscow, 1977.

14. Kuz'min, A. D. and M. Ya. Marov, Fizika planety Venera [Physics of the planet Venus], Nauka Press, Moscow, 1974.

15. Levin, B. Yu., Proiskhozhdeniye Zemli i planet [Origin of Earth and the planets], 4th ed., Nauka Press, Moscow, 1964.

16. Monin, A. S., Istoriya Zemli [History of Earth], Nauka Press, Leningrad division, Leningrad, 1977.

17. Moroz, V. I., Fizika planety Mars [Physics of the planet Mars], Nauka Press, Moscow, 1978.

18. Reeves, G., Proiskhozhdeniye Solnechnoy sistemy [Origin of the solar system], Mir Publ., Moscow, 1976.

19. Runkorn, S. S. and G. Urey, Editors, Luna [The Moon], Mir Publ., Moscow, 1975.

20. Safronov, V. S., Evolyutsiya doplanetnogo oblaka i obrazovaniye Zemli i planet [Evolution of preplanetary clouds and the formation of Earth and the planets], Nauka Press, Moscow, 1969.

21. Shklovskiy, I. S., Vselennaya, zhizn', pazum [Universe, life, intelligence, 5th ed., Nauka Press, Moscow, 1980.

22. Vinogradov, A. P., Editor, Kosmokhimiya Luny i planet [Cosmochemistry of the Moon and the planets], Nauka Press, Moscow, 1975.

23. Vinogradov, A. P., Vvedeniye v geokhimiyu okeana [Introduction to the geochemistry of the ocean], Nauka Press, Moscow, 1967.

24. Voytkevich, G. V., Khimicheskaya evolyutsiya Solnechnoy sistemy [Chemical evolution of the solar system], Nauka Press, Moscow, 1979.

25. Whipple, F., Sem'ya Solntsa [The family of the Sun], Mir Publ., Moscow, 1984.

26. Zharkov, V. N., Vnutrenneye stroeniye Zemli i planet [The inner structure of Earth and the planets], Nauka Press, Moscow, 1978.